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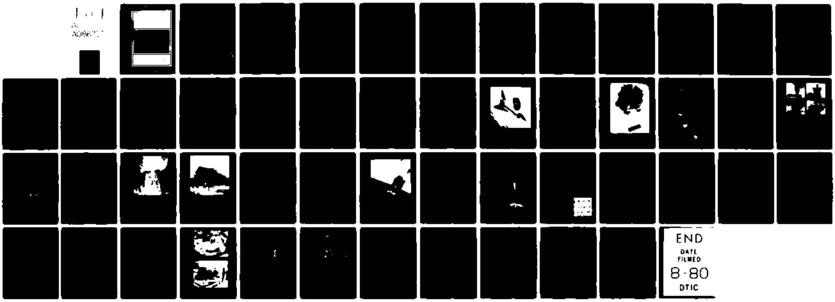

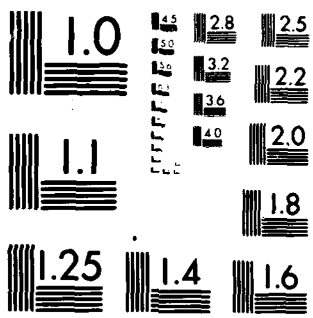

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Requirements, Design and Development of Large Space Antenna Structures

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6 REQUIREMENTS, DESIGN AND DEVELOPMENT OF LARGE SPACE ANTENNA STRUCTURES

Papers presented at the 49th Structures and Materials Panel Meeting held at Porz-Wahn, Germany, 7–12 October 1979.

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PREFACE

The use of telecommunications spacecraft is expected to see a tremendous increase during the next decade. At the radio frequencies most likely to be commonly used, elastic deformation and thermal distortion can have significant effects on the accuracy and efficiency of the antennas. The Structures and Materials Panel of AGARD is therefore proposing to hold a future Specialists' Meeting on Dimensionally Stable Structures for Space to review structural and materials requirements for such antennas, and to discuss design and test methods and criteria. The three papers contained in this publication were presented at the Fall 1979 Meeting of the Panel as guidance in the planning of the forthcoming Specialists' Meeting.

CONTENTS

STRUCTURAL REQUIREMENTS AND CONSTRAINTS OF HIGH GAIN SATELLITE ANTENNAS FOR 30/20 GHz COMMUNICATIONS

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SUMMARY

This paper briefly outlines the types of satellite antennas, the mission constraints and environments for which they must be designed, and the demands placed on the materials and structures of a reflector antenna to satisfy the overall mission requirements. The paper concludes by suggesting areas of research in structures and materials requiring further attention.

1. Introduction

The requirements for communications traffic are rapidly filling the radio frequency spectrum below 14 GHz. The proportional increase in traffic routed through geostationary satellites is already causing frequency co-ordination problems between existing and new systems. In order to accommodate the increasing traffic as well as alleviate mutual interference between systems, it is projected (ref. 1) that regional and domestic trunking of satellite communications traffic in the future will utilise the 30/20 GHz frequency bands. For the efficient use of these frequencies, it is projected that there will be a requirement for multiple high gain narrow beamwidth antennas with low sidelobe levels. A further requirement may be for steerable, switchable and shaped spot beams. For example, figure 1 shows one of many schemes in reference 2 for spot beam coverage of the continental United States of America.

The objective for the satellite antenna designer is to provide antenna configurations capable of satisfying these requirements. The constraints are the interference requirements, the capabilities of the satellite subsystems, environmental effects on the antenna system, and the launch vehicle capabilities. One of the most important requirements for efficient communications at 30/20 GHz is a dimensionally accurate and stable antenna system. The responsibility for the satisfaction of this requirement falls on the structures and materials specialists.

2. Types of Antennas

For the future 30/20 GHz communications missions contemplated, it is projected that three types of antennas have the potential of satisfying the requirements. They are lens antennas, phased array antennas, and reflector antennas. The paraboloid reflector is the most common high gain antenna system used to date. Most of the present developmental work is concentrated on this type of antenna. However, the other two types have certain capabilities that would be difficult to achieve with reflector antennas. A brief description of these other antenna types is therefore included for completeness.

2.1 Lens Antennas

The lens antenna uses the refractive properties of dielectric materials, as well as other techniques, to bend radio frequency (rf) radiation and concentrate it in the desired direction. The concept is analogous to optical lenses and is illustrated in figure 2. An array of rf feeds around the axis of the lens can provide, by appropriate switching in amplitude and phase, multiple steerable and shaped spot beams within the field of view of the lens. Because of their weight, solid dielectric lenses are not used on satellites. Instead, other more mass-effective techniques are utilised to obtain the same effects. The 'lens' in these techniques is an assembly of a number of discrete and guided rf channels. Each channel receives a radiated signal at one surface of the lens and transmits it from the other surface in the desired direction.

One of the main advantages of the lens antenna is that this technique provides comparable gains to reflectors without any blockage from the feeds and their supporting structures. In a lens antenna, the sidelobe levels can be controlled more effectively than in a reflector. The lens is also less sensitive to dimensional inaccuracies. One of the first communications satellites to use lens antennas is the United States' DSCS III series, currently being built by the General Electric Company. The lenses are fabricated by employing wave guide channels to direct and synthesize the beams.

The disadvantages of lens antennas are the complexity of the lens structure and its weight. This is in addition to the complex electronics that is required to provide the beam shaping and steering capability. There is also a general lack of experience in the design of lens antennas for satellite applications. In view of their potential benefits, however, some development work is underway (ref. 3).

2.2 Phased Array Antennas

The phased array antenna, conceptually illustrated in figure 3, is made up of an array of rf radiating elements. By adjusting the amplitude and phase of the signal in each of the elements, a desired beam can be obtained. A number of shaped spots may also be synthesized.

The major advantage of the phased array antenna is that its beam is amenable to electronic steering over large angles through control of the amplitude and phase of the signal applied to each element. At the same time good sidelobe control can be achieved. Of the three types of antennas, the phased array is the least sensitive to dimensional inaccuracies in its support structure.

A phased array antenna is a less efficient radiator than a reflector antenna, resulting in inefficient use of the available mass, power and platform area on the satellite. Due to the large number of radiating elements and the associated feed network, the reliability is also less in comparison to a reflector antenna. However, in view of the capability of a phased array antenna to steer beams over large angles, the antenna has been used in several satellite missions. One such mission is the planned Tracking and Data Relay Satellite System (ref. 4) which will use a phased array antenna for S-band communications.

2.3 Reflector Antennas

The reflector antenna is the most common high gain antenna used for communications on satellites. In the simplest form of a reflector antenna, an rf feed is placed at the focus of an axisymmetric paraboloid reflector to provide a collimated beam. The concept is illustrated in figure 4(a).

The prime reason for the popularity of the reflector antenna is the relatively simple structure. It is ideally suited to provide a single high gain spot beam. Multiple spot beams require a cluster of feeds at the focus. This leads to loss in performance due to increased blockage of the reflected beam by the feeds and their supports. The problem can be alleviated by resorting to an off-set fed reflector antenna as illustrated in figure 4(b). The off-set fed reflector is derived by retaining only a portion of an axisymmetric reflector. The rf feed at the focus is configured to illuminate only the retained portion of the axisymmetric reflector.

Three types of reflectors can be considered for satellite applications. One is the prefabricated solid reflector, the second is the unfurlable reflector and the third is the type that is assembled in orbit. Extensive flight experience already exists for the prefabricated solid reflector. Unfurlable reflectors have already been used successfully on the ATS-6 and Fleetsatcom satellites, and are planned for the Tracking and Data Relay Satellites (ref. 5). With the imminent development of the Space Transportation System, large reflectors requiring erection in space are currently receiving considerable attention (ref. 6).

3. Mission Environment

The satellite antenna is subjected to a variety of environments between the time the hardware is fabricated through to the end of the satellite mission.

The antenna first undergoes a number of component and system tests on the ground. After testing, it may be stored for a period of time before it is launched. Associated with this are gravity and handling loads, the terrestrial temperatures, and the humidity. During launch the antenna is subjected to high dynamic and static loads (magnitudes depend on the chosen launch vehicle and the satellite design), and rapid depressurisation. The ambient pressure drops to near absolute vacuum ($\sim 10^{-14}$ Pa) when the satellite is placed in a geostationary orbit.

When the satellite is on-station in the geostationary orbit, the antenna experiences continuous thermal cycling as it makes one revolution every 24 hours relative to the sun vector. This contributes to large temperature gradients in the antenna. The solar radiation flux can vary between 1.28 to 1.42 kW/m^2 depending on the season of the year and the solar activity. During the equinox seasons, the antenna is eclipsed from the sun by the earth every 24 hours for up to 72 minutes. During the eclipse, the antenna temperature may reach very low values as the antenna structure loses heat to cold space which is near zero Kelvin. When entering and exiting from an eclipse, the antenna is subjected to thermal "shocks" causing rapid changes in temperature and high thermal gradients.

The antenna material is also subjected to ultraviolet radiation and particle bombardment in the space environment.

4. Structural Requirements of Satellite Reflector Antennas at 30/20 GHz

The size of the antenna is governed by the mission requirements. These are the required gain, the number of spot beams and their footprint shapes on the surface of the earth, and the interference constraints. The over-riding constraint on size is the available dimensions for the payload in the chosen launch vehicle. The Ariane launch vehicle has a shroud diameter of 3.0 meters, while the Space Transportation System's shuttle orbiter payload bay has a diameter of 4.5 meters. Another indirect, but important, constraint on size is the present capability of satellite pointing systems. A 4.5 meter diameter reflector at 20 GHz provides a beamwidth of approximately 0.25°. For efficient use of this communications beam, an antenna pointing accuracy of at least one tenth of the beamwidth should be provided. A pointing accuracy of 0.025° is about the present limit of satellite attitude control systems using rf tracking methods.

The dimensional accuracy requirement of antennas for 30/20 GHz communications is extremely stringent. The extent to which the performance of a reflector type antenna at higher frequencies is affected by contour deviations from the optimum may be illustrated by the following example: The loss in antenna gain for a 1.25 mm rms deviation from the intended parabolic contour is approximately 0.001 dB at 0.3 GHz, 0.1 dB at 3 GHz and 10 dB at 30 GHz. In order to provide a specified flux density on the ground, the loss in antenna gain must be compensated by an increase in transponder power. The satisfaction of the power requirement will result in a more expensive satellite, both to build and to launch. Moreover, the reduction in gain is usually accompanied by an increase in sidelobe levels. This effect contributes to inefficient use of the frequency spectrum as the sidelobes interfere with adjacent communications systems sharing the same frequency bands. A more detailed treatment of the effects of antenna profile inaccuracies is given in reference 7. The following table extracted from reference 8 gives the dimensions, the communications frequencies and tolerances of some existing and future reflector type satellite antennas.

	Diameter meters	Frequency GHz	Tolerance rms mm
OTS spot beam	0.72	11.7	0.15
Marecs	2.0	1.65	0.5
ATS-6	9.1	8.1	1.52
TDRSS	4.8	15.1	0.56
JPL Experimental	30	15	1.0
Grumman Broadcast	300	0.79	10.0

Any deviation, both on-axis, and off-axis, of the feeds from the focus of the paraboloid reflector also causes a degradation in antenna performance. The effect of on-axis defocussing is equivalent to contour deviations of the reflector surface. Off-axis defocussing has the additional disadvantage of introducing pointing errors in the reflected beam. From frequency re-use considerations, rf radiation is linear or circular polarised. In the case of linear polarisation, the communications system performance is adversely affected by twisting of the feeds relative to the reflector. Hence, another structural requirement is for an accurate and stable feed support structure.

Other antenna structural requirements include: low mass, to obtain the most payload in orbit; high strength, to withstand both launch loads and ground handling; and high stiffness, to withstand launch loads and to miminise interactions with the satellite control system. The antenna design must be capable of being verified in the 1 g environment on the ground. It must be capable of maintaining its designed geometric configuration in the space thermal environment. To meet this last requirement, an important design factor is the choice of materials which have low coefficients of thermal expansion and high thermal conductivity. Additional thermal protection is sometimes obtained from multilayer insulation blankets made of metallised plastic. These should be incorporated into the antenna structure so that they do not interfere with the rf performance of the antenna. The vacuum environment of space leads to outgassing by materials. The constituents and quantities given off must not be detrimental to the structure itself as well as to other sensitive components of the satellite. Typically, the sensitive components are surface finishes for thermal control, solar cells and sensor apertures of the attitude control system.

The developments in advanced composite materials have been significant for satellite communications. The high strength and stiffness to mass ratios of these materials and their ability to meet the prescribed coefficients of thermal expansion offer the potential for lightweight dimensionally accurate antenna structures. This potential has already been exploited in past missions and extensive development work aimed at future applications is continuing. References 9 to 12 provide examples of these activities. Figure 5, extracted from reference 11, illustrates the potential for improved dimensional stability of space structures fabricated from advanced composite materials.

5. Suggestions for Research and Development

The purpose of the following suggestions is to contribute to improved dimensional accuracy of future satellite antenna systems. The factors that contribute to dimensional inaccuracies are the structural design process, the physical properties of the constituent materials and the fabrication process that is utilised.

The structural design process involves the use of software packages for predicting the response of the modelled antenna structure. Inaccuracies in the model can lead to inaccuracies in the design. Composite material lay-ups for antennas are generally anisotropic. Development of tested finite element models of typical anisotropic lay-ups used for antennas would contribute to reducing the errors associated with the design process.

The properties of advanced composites can change with the environments to which they are exposed. There is a shortage of reliable data on the composite materials that are used in satellite applications. Characterisation of both the constituent materials, as well as the mixtures, by appropriate mechanical, chemical and space environmental tests would be helpful to the antenna designers.

The fabrication process utilised affects the dimensional uncertainties. In the fabrication of composite material antennas, cure processes sometimes result in built-in residual stresses. These may relieve themselves over the mission life of the antenna and cause dimensional changes. Also, a fabricated antenna may be stored on the ground for as long as five years before it is launched. The terrestrial environment, particularly humidity, is known to cause creep in some composite materials. Development of processes that make the structure insensitive to the expected space and terrestrial environments would contribute to dimensional accuracy.

6. Conclusion

This paper has addressed the importance of dimensionally stable satellite antennas for 30/20 GHz communications. The benefits, however, can range from more efficient use of frequencies below 30/20 GHz to making possible effective inter-satellite communications in the EHF band. In summary, dimensionally accurate and stable satellite structures will permit increased efficiencies to be achieved and hence expand the range of potential services realisable with satellite communications systems.

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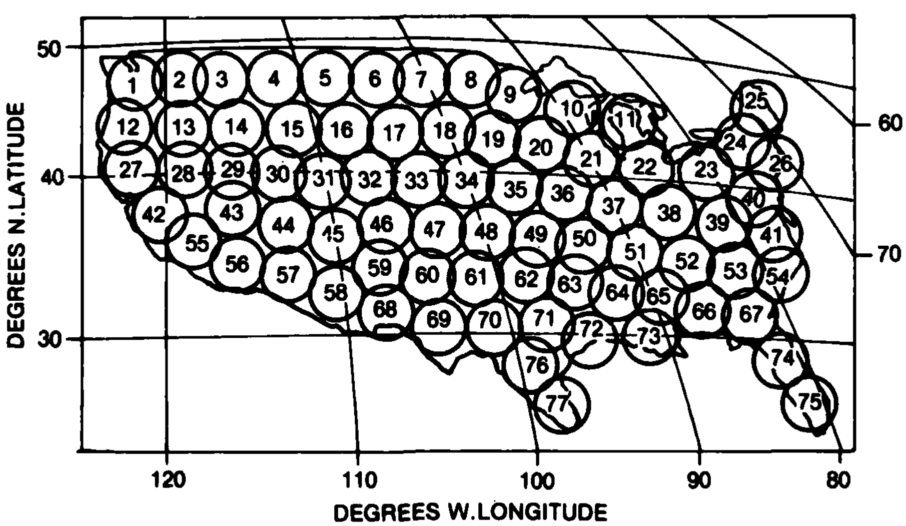

Figure 1 A scheme for spot beam (0.5^{o} beamwidth) coverage of the U.S. with 77 beams from geostationary orbit

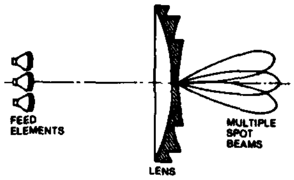

Figure 2 Lens antenna concept

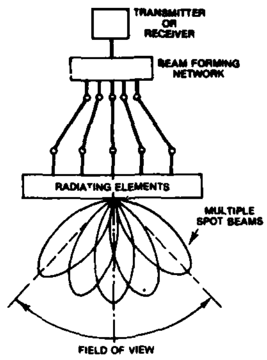

Figure 3 Phased array antenna concept

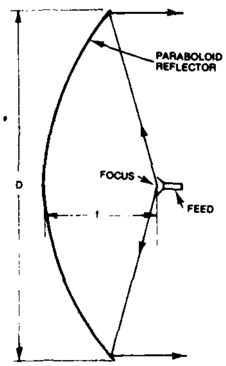

Figure 4(a) Centre fed parabolic reflector antenna concept

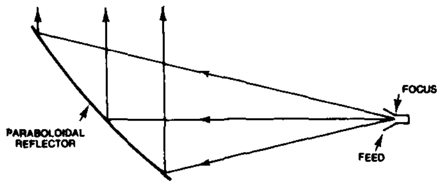

Figure 4(b) Off-set fed parabolic reflector antenna concept

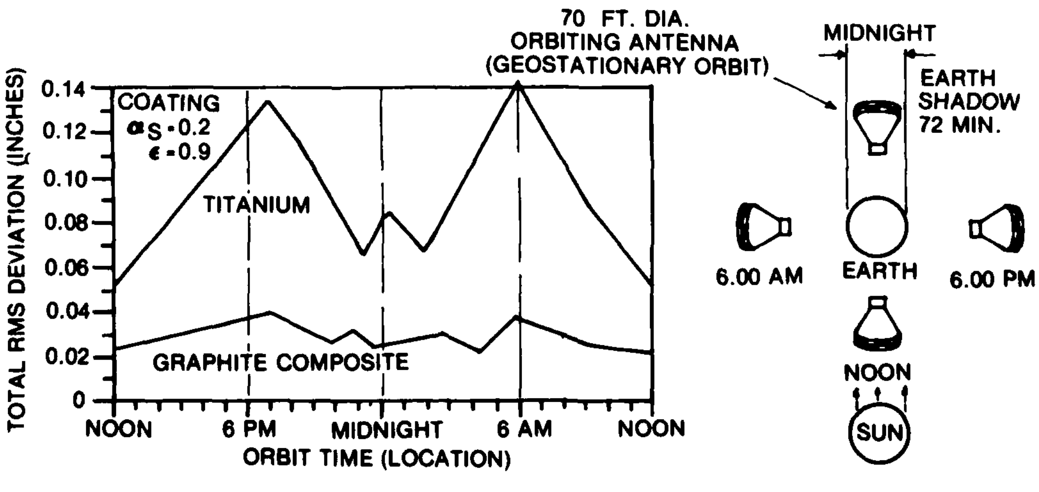

Figure 5 Predictions of thermally induced contour deviations of a 70 ft (21.3 m) aperture antenna in geostationary orbit for structure fabricated with titanium or graphite re-inforced composite material

NASA TECHNOLOGY FOR LARGE SPACE ANTENNAS

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ABSTRACT

Recent studies conducted by both the National Aeronautics and Space Administration (NASA) and United States (US) industry indicate that potential applications exist for large space-based antennas in the areas of communications, radio astronomy, and Earth observations. The deployable antenna, based on its demonstrated success in the smaller aperture range, provides a potential capability for satisfying a significant number of these space-based applications. In this paper, some leading concepts for deployable antennas are described, an assessment of the state of the art in deployable antennas is presented, and a discussion on the technology development program for two deployable antenna concepts that are responsive to the antenna mission requirements as presently defined in the NASA mission model which describes potential applications. Specifically, these concepts are the offset wrap-rib and the maypole (hoop/column) configurations.

1. INTRODUCTION

The advent of the Space Transportation System (STS), with its capability for delivering scientific payloads to Earth orbit, has created the opportunity for developing a host of large space systems. In that regard, the Large Space Systems Technology (LSST) Program of the National Aeronautics and Space Administration (NASA) has as a primary objective the development of technology that will lead to the realization of cost-effective, STS-compatible, large space systems. Since many of the large space systems proposed for future missions utilize large space antennas, the LSST Program has identified antenna technology as one of the major concept development activities. These potential missions consist of applications in communications, Earth observations, and radio astronomy (refs. 1 and 2).

The LSST approach for the development of technology for large space antenna systems starts with the synthesis of systems whose requirements will satisfy several classes of potential users that have been identified by the NASA Office of Aeronautics and Space Technology (OAST) mission model. The technology requirements associated with the synthesized missions are then evaluated with respect to state of the art and projected capabilities so that the technology gaps can be the basis of program development.

Evaluation of the state of the art for large space antenna structures identified the self-deployable class of antennas as offering great potential for achieving technology readiness for early space flight experiments, demonstrations, and applications. In particular, two concepts with potential for the classes of missions identified by the NASA mission model are the offset wrap-rib and maypole (hoop/column) deployable antennas (ref. 3).

This paper describes some of the leading deployable antenna concepts; summarizes the state-of-the-art review for large deployable space antenna structures accomplished by the LSST Program and discusses the antenna technology development of the offset wrap-rib concept and the maypole (hoop/column) concept.

2. DEPLOYABLE ANTENNA CONCEPT DESCRIPTIONS (REFERENCE 3)

Concepts for deployable antennas that have been developed to the point of detail design include: the advanced sunflower precision antenna from TRW; the radial rib antenna and the maypole (hoop/column) antenna from the Harris Corporation; the wrap-rib antenna from Lockheed Missiles and Space Corporation (LMSC); and the parabolic erectable truss antenna from the General Dynamics Corporation (GDC). These concepts are well known and are documented in the open literature. For familiarization purposes, the salient features regarding each concept are briefly summarized below.

2.1 TRW Advanced Sunflower Precision Antenna (References 3 and 4)

2.1.1 Summary

TRW has demonstrated the feasibility of the advanced sunflower concept with a 2.1-m mechanical model and has developed the preliminary design for a 7.3-m diameter precision-deployed antenna (fig. 1) capable of operation at frequencies up to 60 Gigahertz (GHz) and above. The antenna design provides radio frequency (RF) efficiency of 70%, with a beam pointing error less than 0.40°. The estimated 72.5 kg mass for this design includes the subreflector, support structure, and communication beam autotrack feed package. The deployed natural frequency is estimated at 5 Hertz (Hz). The mechanical design features graphite/epoxy (Gr/E) composite hinged-panel construction. The design is capable of withstanding conventional or STS launch loads.

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2.1.2 Concept Description

This deployable concept provides a large, lightweight, precision-contour parabolic antenna. The concept was developed for a shaped Cassegrain antenna application with a single, high-efficiency data beam/multimode autotrack system. The antenna is constructed of graphite/epoxy facesheets and an aluminum core sandwich to provide an extremely lightweight system. The antenna mass is 67.6 kg for a 7.3-m diameter design, including thermal paint and the stowage release mechanism. The center section is a one-piece honeycomb sandwich construction, and the folding panels are rigid honeycomb sandwich. The main panels hinge from a support ring under the center section. The two intermediate panels lie between, and are connected to, the main panels and to each other with two or more hinges. The hinges have adjustable stops to locate the panels accurately in the deployed configuration. Springs are used in the hinges to drive the panels to the deployed position. Adjacent inboard hinges of the main panels are interconnected with a compound universal coupling to ensure synchronization of all panels during deployment (fig. 2). The deployment rate is controlled by either a damping device or a geared motor. The furled antenna is restrained by a pin puller, which is ordnance released, and supported on one of the tiedown fittings. Although Figure 3 shows six main panels hinged from the fixed center section, the number of main panels can be varied as required to optimize the diameter and height of the stowed antenna.

2.2 Harris Corporation Radial-Rib Antenna (References 3 and 5)

2.2.1 Summary

During the past 10 years, the Harris Corporation has developed a radial-rib, double mesh, deployable antenna concept for space application. This basic design was refined through the Advanced Applications Flight Experiment (AAFE) Program as the emphasis was placed on a minimum weight configuration suitable for operations at Ku-band frequencies (ref. 5).

This concept was selected for the Tracking and Data Relay Satellite System (TDRSS), and the Harris Corporation has recently completed the fabrication and testing of the 4.8-m TDRSS antenna. The mechanical, thermal, and RF performance of this concept has been demonstrated on the TDRSS Program. The analytical models used for design and performance predictions have also been verified.

2.2.2 Concept Description

The radial-rib antenna design is illustrated in Figure 4. The antenna utilizes 18 graphite fiber reinforced epoxy (GFRE) ribs to shape and support the mesh surface. The number of ribs is based on a trade-off considering surface tolerance and weight. As the number of ribs increases, the surface error decreases, while weight increases. The minimum number of ribs consistent with the surface tolerance requirements is, therefore, usually selected. The ribs are circular in cross section tapering from a 3.8-cm diameter at the root to a 1.9-cm diameter at the tip. The rib is constructed of four plies of graphite which results in a wall thickness of 0.04 cm. The mesh surface is attached to the ribs by adjustable standoffs; therefore, the tolerance on rib shape is not a critical parameter. The ribs are typically fabricated to a constant radius of curvature rather than a parabolic shape.

The mesh consists of gold-plated, molybdenum wire which is knitted into a soft (low spring rate), elastic mesh. The mesh opening size can be varied to ensure adequate RF reflectivity for a given requirement. The required antenna surface tolerance is achieved with minimum weight through the use of a secondary drawing surface technique. This technique is illustrated in Figure 5. A series of circumferential quartz cords is attached to the back of the ribs by adjustable standoffs. A second series of quartz cords is attached to the front mesh surface as shown in Figure 5. These "front cords" run parallel to the "back cords." The front and back cords are connected by a series of stainless steel tie wires. By properly adjusting the rib standoff heights, the back cord geometry, and these individual tie wires, a very accurate surface contour is achieved.

The feed support structure (fig. 6) provides the primary structure for the stowed antenna as well as serving as the structure for support of the dual frequency feed and subreflector. This support structure consists of a 6-member GFRE truss structure and a single skin quartz radome structure. The subreflector is a sandwich construction of kevlar skins and a kevlar honeycomb core.

Thermal control of the antenna ribs and feed support structure is accomplished with multilayered insulation blankets. These blankets utilize inner layers of embossed aluminized Kapton and an outer layer of Kapton.

The RF measured results of the TDRSS antenna indicate that all the performance requirements at Ku-band have been achieved.

2.3 Harris Corporation Maypole (Hoop/Column) Antenna (References 3 and 6)

2.3.1 Summary

The maypole (hoop/column) antenna concept (ref. 6), illustrated in Figures 7, 8, and 9, has been developed to the point of a preliminary design for sizes up to 100 m. The 1.8-m demonstration model (fig. 8) was used to verify the basic conceptual design and to aid in development of the deployment kinematics of the design. The preliminary design has been complemented with the development of analytical techniques for prediction of antenna performance of these large structures.

2.3.2 Concept Description

The major elements of the maypole (hoop/column) concept are delineated by Figure 7. The fundamental elements of the support structure include the hoop; upper, lower, and center control stringers; and the

telescoping mast. The reflector consists of the mesh, mesh shaping ties, secondary drawing surface, and the mesh tensioning stringers. The basic antenna configuration is a type of maypole with a unique technique for contouring the RF reflective mesh.

The hoop's function is to provide a rigid, accurately located structure to which the reflective surface attaches. It is comprised of 40 rigid sections which articulate at hinges joining adjacent segments. These segments consist of two tubular, graphite fiber members parallel to each other and attached to a long hinge member at each end. Torsion springs located in each hinge supply the total energy required to deploy the hoop.

The central column, or mast, is deployable and contains the microwave components and control mechanisms. It consists of tubular graphite/epoxy shell members that nest inside each other when stowed. Aside from housing various components, the mast provides attachment locations for the reflective surface and the stringers.

Five sets of stringers are used on the maypole (hoop/column) concept. Three of these sets are used for hoop deployment and its control; the other two sets are used for mesh shaping. The hoop-control stringers are located at the upper end, the center, and the lower end of the extendible mast; they extend radially outward to their attachment positions at the hinges of the hoop. The upper and lower control stringers accurately position the hoop throughout its deployment (fig. 9). The center control stringers are used for rate control during deployment and for moving the hoop joints toward the mast, against their spring forces, during the automated stowing sequence. The remaining two sets of stringers (mesh tensioning stringers) are located just above the lower control stringers and are used to shape the reflective surface into the proper contour. All of these stringers are made of quartz cords for high stiffness and thermal stability.

Preliminary evaluations indicate the mesh tensioning stringers can be effectively utilized to actively adjust the orbital surface contour of the antenna. The feasibility and technology for such active contour control will be addressed during the LSST technology program.

The reflective surface (illustrated in figs. 10, 11, and 12) is produced by properly shaping a knitted mesh fabric. The mesh consists of gold-plated molybdenum wire. The mechanism that permits shaping of the mesh consists of numerous radial quartz stringers to which the mesh is directly attached (mesh surface stringers) along with a similar set of stringers (secondary drawing surface stringers) positioned beneath them. Short ties (mesh shaping ties) made of fine wire connect the RF mesh surface stringers to the secondary drawing surface stringers as shown. When the mesh tensioning stringers are positioned, they in turn apply tension to both the secondary drawing surface stringers and the mesh shaping ties to produce an essentially uniform pressure distribution on the mesh which results in a good approximation of a parabolic curvature. This configuration for a single gore element is shown in Figure 12.

Two groups of drive mechanisms are used in the maypole (hoop/column) concept. One group, used to extend the mast, consists of one basic set of mechanisms for each section of the telescoping mast. The second group of drive mechanisms is used to adjust the control stringers and consists of motor-driven spools to which the stringers are attached. There are five sets of spools, one for each group of stringers. The spools are used to retract and discharge the stringers during the deployment and stowing sequences and are positioned around the mast in the locations described for the stringer attachments. Deployment of the antenna is fully controlled. A unique feature of the design is the ability to restow the antenna. This capability allows maximum utilization of the Shuttle capability to retrieve the antenna for ground evaluation and/or for refurbishment for future flights.

2.4 Lockheed Missiles and Space Corporation (LMSC) Wrap-Rib Antenna (Reference 3)

2.4.1 Summary

LMSC has developed the wrap-rib antenna to the point of numerous flight applications for many different sizes of antennas. The best known application is the Applications Technology Satellite 6 (ATS-6) spacecraft which uses a 9.1-m parabolic, wrap-rib antenna (fig. 13) operating up to and above 8 GHz. The ATS-6 antenna, made with aluminum ribs and conventional thermal blankets, represents a technology that is about 12 years old. Recent developments using this concept have resulted in a manufacturing capability for fabricating wrap-ribs from composite materials with extremely low coefficients of thermal expansion (ref. 7). New materials and processes for manufacturing mesh have been developed recently, and the analytical capability for the detail design of the structure has been improved recently. These developments have made it possible to design, build, and predict antenna performance for wrap-rib structures up to several hundred meters in diameter, and perhaps larger, for operation up to, and possibly above, X-band.

2.4.2 Concept Description

The wrap-rib antenna configuration is based on a number (variable) of radial ribs or beams which are cantilevered from a central hub structure. Each of the ribs is attached to the hub structure through a hinge at the root of the cantilever. This radial spoke system provides the mounting for the antenna radiating elements or reflector surface, depending on whether an array or a reflector is desired. For parabolic or other curved reflectors, the ribs are formed to the required shape and reflective pie-shaped gores of membrane material, which is usually knitted or woven fabric, is attached between the ribs (ref. 8).

The rib cross section and material are chosen to permit the elastic buckling of the ribs. This is to allow the ribs to be elastically wrapped around the hub structure in the stowed package configuration (fig. 14). In the antenna stowing process, the ribs with the mesh gores folded between them are rotated about the rib hinges until the ribs are tangent to the hub. After this initial rotation, the ribs are wrapped completely around this section. The RF reflective mesh gores are allowed to form a package between the ribs.

Antenna deployment is accomplished for small size systems (less than 25 m in diameters) by release of strain energy in the ribs. For antennas of this size, the stowed package is contained by a series of hinged doors which are held in place by a restraining cable. Deployment occurs when the cable is severed. For the large size antennas where deployment reaction is a problem, a deployment restraint system is employed that uses a tape and pully system (fig. 14). With this system, a tape is placed between each rib, such that the tape under tension keeps each rib wrapped around the hub. For deployment, a motor drives a large gear which in turn rotates the tape take-up reels. The ribs deploy as the tape is reeled up. A constantly slipping clutch is located in each tape reel drive to limit the tape tension and allow positional and speed variations from rib to rib and during deployment.

2.5 General Dynamics Corporation (GDC) Parabolic Erectable Truss Antenna (References 3 and 9)

2.5.1 Summary

GDC has developed the parabolic erectable truss antenna (PETA) concept to the point of a hardware demonstration of a 5.2-m diameter model (fig. 15). This model, and other smaller models, successfully demonstrated the antenna's self-deployment characteristics, provided verification of the mathematical models, and provided measured mechanical and RF performance information (ref. 9). This concept has been under development for more than 10 years; however, the latest version is based on using structural composite materials with low coefficients of thermal expansion.

2.5.2 Concept Description

The PETA concept is a basic building block used in numerous combinations to achieve the desired shape and size of antenna structure. The basic element is a deployable tetrahedron truss that is hinged by spider links at each corner (fig. 16). Each tetrahedron forms one truss bay. The number of bays can vary from 4 to 10, or more, across the major diameter of the antenna structure. This configuration is the basis of the support structure for the RF reflective mesh and feed support system. Components of the antenna structure have the same basic configuration design, regardless of the number of bays. Therefore, as the number of bays increases, for a given diameter, the number of mesh support points increases and the antenna surface improves.

Deployment of the basic tetrahedron is made possible by hinging of the struts at their centers with carpenter tape hinges (fig. 17). This type of hinge provides sufficient strain energy to accomplish deployment with an excellent mechanical lock-up in the deployed configuration.

Various materials including aluminum, titanium, and graphite/epoxy have been evaluated for application to the basic truss design. The choice of materials strongly influences the weight, cost, thermal distortion, and mechanical packaging efficiency of the antenna. Aluminum tubes provide the lowest cost material, but result in relatively high weight and thermal distortion. Perforated-wall aluminum tubes reduce thermal distortion and weight at some increase in cost. Perforated-wall titanium tubes produce low thermal distortions with weight slightly in excess of perforated aluminum tubes. Graphite/epoxy tubes produce a very lightweight truss with almost twice the packaging ratio of the perforated aluminum version.

The RF reflective mesh is supported across each bay by a series of tension ties and a webbing attachment system that interfaces the tension ties with the mesh. The tension ties are attached to standoffs at each spider and span each bay with a simple grid pattern. The webbing system in turn is attached to the tension ties at a number of points to provide a finger pattern to which the mesh is attached. The resulting configuration of the mesh is eight flat-surface elements, within each bay, that collectively approximate a parabolic surface.

Because of the inherent stiffness of the basic truss structure, attachment of the feed support structure, or any ancillary equipment installation, may be made at the center, at the edge, or at intermediate locations without significant penalty. Because of this feature, an offset feed system can be used without major modification to the current designs.

3. STATE OF THE ART TECHNOLOGY ASSESSMENT

The technology to be developed for the LSST antenna systems represents the gap between mission requirements and current capability. Once the requirements for the LSST focus mission had been developed, an assessment of the existing and projected capability was conducted. In the case of deployable antenna technology, the results of previous antenna development activity and technology assessment studies were determined to be sufficient for understanding the present state of the art.

The determination of current and projected performance for deployable reflector antennas was based on: (a) surface precision as a function of deployable diameter, (b) configuration applicability for offset feed applications, (c) the maturity of concepts and designs under consideration, and (d) the time frame required for development of the technology to the point of application. Estimates of deployable antenna surface quality as a function of size are given in Figure 18 (ref. 10). Data for the characterization was obtained from References 3, 4, and 6.

Precision deployable antenna surface accuracy is given by line segments A and B of Figure 18, and can be read directly as a function of diameter. The surface accuracy to diameter ratio given by line segment A comes from estimates of current capability that are based on the performance of scale models, critical components for intermediate size antennas, and analytical estimates of performance for the larger sizes. Line segment B represents estimates of performance for the next level of technology development that is based on extensive improvements of current designs, such as better mechanical packaging efficiency and active surface sensing and figure control. The upper frequency range of operation for these antennas is based on an equivalent surface roughness of approximately $\lambda/40$ and $\lambda/30$, respectively, where λ is

wavelength of operating frequency. This range is given as a function of diameter for purposes of reference. The estimated surface accuracy is given for the "as manufactured" case and does not include on-orbit thermal distortion, which is a function of the antenna configuration, the orbit, and the materials used for construction. Therefore, the usable frequency for the surface quality shown is somewhat lower than indicated, depending on the particular application.

The surface accuracy of the mesh deployable antennas is given by line segments C, D, and E of Figure 18, and can be read directly as a function of diameter. The surface quality represented by line segment C is based on a composite of demonstrated and estimated performance for current mesh deployable antenna capability. The demonstration of this technology is based on results of models, components, and full-scale testing on analytical predictions of full-scale performance, and on flight experience for some designs. Line segments D and E represent estimates for performance for the next two levels of technology development which are based on the assumption that the ratio of surface quality to deployed diameter can be kept constant. The upper frequency range of operation for the indicated surface precision, based on an equivalent surface roughness of approximately $\lambda/20$, is given as a function of diameter for purposes of reference. The surface qualities given are for the "as manufactured" base which includes approximation loss and manufacturing tolerances, but does not include thermal distortion and interaction of the structure with the control system and external disturbances; because these considerations are dependent on the configuration, materials used, and the application. Therefore, actual on-orbit operating frequencies are somewhat less than indicated.

In order to characterize on-orbit mesh deployable antenna performance, estimates of worst-case thermal distortion were obtained for the Harris maypole (hoop/column) and the GDC/Convair PETA and plotted as a function of surface precision and diameter. The reduction of operational frequency as a consequence of accounting for the thermal distortions is evident. However, the actual antenna surface quality for a specific application may be different because of the structural configuration, the materials used, and the particular service environment.

4. ANTENNA TECHNOLOGY DEVELOPMENT APPROACH

The LSST program was created by the NASA to identify the technology requirements for the classes of potential mission applications and to manage an intercenter technology development program. The basic objective of the LSST program is to provide systems level technology for evolving cost-effective STS-compatible antennas and platforms that will be automatically deployed, assembled, or fabricated in orbit to perform missions in the 1985 to 2000 time period.

The LSST approach for the development of technology for large space antenna systems starts with the synthesis of systems whose potential performance will satisfy several classes of potential users that have been identified by the NASA mission model. The critical technologies associated with the synthesized missions are then used to focus the technology developments within the program. These specific technology challenges and goals have resulted from the stringent performance requirements projected for the large structural systems operating in the space environment as well as the size limitations imposed by the STS payload compartment.

The development of large space system antenna technology within the framework of the LSST program (ref. 10) affords an opportunity for both government and industry to: (a) generate new and innovative concepts and designs, (b) further develop existing concepts which potentially offer significantly improved performance capabilities with respect to the state of the art, and (c) extend the performance of proven designs to new and unexpected levels of performance. This opportunity for the development of the subject technology has materialized as a consequence of the expectation of the STS and the desire of the NASA to demonstrate and exploit the capability of large space antenna systems for a host of meaningful applications.

4.1 NASA Mission Model

The determination of requirements for the development of technology for large space systems is dependent on the identification of potential space-flight missions and the degree to which these missions can be defined by the user offices. The user offices proposing future missions, at this time, include the NASA Office of Space Science (OSS), Office of Space and Terrestrial Applications (OSTA), and the Office of Aeronautics and Space Technology (OAST). Figure 19 represents a summary of potential missions, utilizing large space systems for the 1985 to 2000 time period. The particular missions identified by the mission model that require advanced antenna technology are the precision shaped surface structures. It is anticipated that the number of potential missions will increase while the requirements become more demanding as the technology for large space antenna systems is further developed. The NASA mission model will be maintained to account for the addition/deletion of potential missions, as well as the changes and reemphasis in the missions requirements.

4.2 LSST Focus Missions

In order to focus the development of technology for proposed future missions, the LSST Program Office developed the concept of "focus missions." The focus missions approach is to broaden the narrow, individual mission requirements into a broader matrix of requirements and thereby enhance the probability of developing concepts of broad applicability as opposed to a concept that satisfies only a particular set of requirements. The LSST focus missions were initiated by selecting characteristic classes of missions whose potential performance satisfy a large number of specific missions presently identified. Tables I and II identify the near- and far-term focus missions presently selected.

5. TECHNOLOGY DEFINITION

The evaluation of current and projected capability for mesh deployable antennas suggests that the requirements for near-term antenna applications can be satisfied in terms of size and frequency. However, satisfaction of these requirements is based on the anticipated performance of antenna concepts and designs that require additional technology development.

The specific concepts identified as having the potential capability of satisfying the LSST requirements are under development by the LMSC and the Harris Corporation. The LMSC wrap-rib antenna has successfully demonstrated its axisymmetric design capability with flight applications--the most notable being the ATS-6. This cantilever rib type configuration is amenable to offset feed applications required for near-term LSST focus missions. The maypole (hoop/column) antenna concept defined by the Harris Corporation offers the potential of large size apertures using a modified TDRSS antenna surface shaping approach in conjunction with a cable stiffened support structure.

5.1 Technology for Offset Wrap-Rib

5.1.1 Summary

The offset wrap-rib deployable antenna concept is shown in Figure 20. The design and analyses performed to date indicate that the proven wrap-rib design can be readily adapted to an offset geometry. The adaptation retains the benefits of high density packaging, lightweight, and growth potential for offset-fed antennas of the wrap-rib concept in sizes up to 300 m.

Geometrically an offset reflector is described by a paraboloid where the geometric centerline is not coincident with the parabolic axis of symmetry (ref. 11). In order to gain the electrical advantages of reduced blockage, the parabolic axis and the focal point must be located external to the section aperture. This section can most easily be visualized by forming a large paraboloid of diameter D and then passing a cylinder, with a parallel axis of symmetry, through the paraboloid (fig. 21). If the cylinder has a diameter d less than D/2 and its radius is common with the radius of the parabola, the section of the paraboloid bound by the cylinder is representative of the desired offset reflector surface.

The difference in configuration between the offset and axisymmetric antennas is significant in that the offset antenna has only one plane of symmetry and the associated feed support structure must be cantilevered from the hub structure. The lack of symmetry means that only two ribs are similar for the offset antenna and the cantilevered deployable feed support structure is one-half the diameter of the antenna.

5.1.2 Technology Development

The RF requirements for the large offset antennas, i.e., 11 GHz at 100 m, dictate the need for application of composite materials for the rib structure to maximize stiffness to weight ratio and to minimize thermal distortions. Temperature gradients develop in the ribs due to shading of a portion of a rib either by an adjacent rib or by other spacecraft members (ref. 12). These gradients cause deflections normal to the reflector surface; and, therefore, have a significant influence on the antenna performance. Early wrap-rib antenna designs used aluminum ribs, but, as the need for larger diameters and higher radio frequencies evolved, the search began for improved materials. LMSC is currently building and evaluating a 15-m diameter graphite/epoxy rib antenna (X-band) (fig. 22). The thermal losses that develop with this antenna will be significantly less than for an aluminum rib antenna of the same size and frequency. Additional improvements in antenna performance can be expected from using metal matrix composites for the ribs because of their excellent thermal conductivity, low thermal expansion, and immunity to moisture absorption (ref. 13).

The results of a trade study accomplished by the LMSC for a 9 GHz antenna (typical for any frequency) are shown by Figure 23, in which the diameter increases are seen to give increasing antenna gain for each material up to a certain point. Without thermal distortion due to rib thermal gradients, the gain would increase indefinitely. When the thermal distortion effects become large, the antenna gain starts deviating from the theoretical. The peaks of these curves, of course, represent optimum diameters to achieve the largest gain for that material. The graphite aluminum (Gr/Al) is seen to be the only material to out perform Gr/E.

The RF reflective mesh used by the LMSC for deployable antennas includes woven and knit fibers (fig. 24). Knitted meshes characteristically do not have continuous strands or reflective wires which run in two orthogonal directions (ref. 14). Therefore, electrical conduction is accomplished by intimate contact in the course direction (perpendicular to the wrap). For a knitted wire, all that is required is that a certain minimum preload be maintained by the mesh during the worst-case thermal conditions.

For knitted nonmetallics with a metallic plating, such as copper plated dacron which has been used for early flight applications, the plating itself provided the continuity through the joint. This can be a problem if the plating is fragile or susceptible to cracking because a nonconductive surface oxide could develop prior to launch. Since the metal plating will exhibit potential properties representative of the metal used, high operating temperatures would result unless a thermal control overcoat is used. The use of silicons or Teflon over the metallic plating sufficiently increases the emittance of the surface to reduce the upper temperature.

A significant difference between the woven and the knitted mesh is the stiffness. For example, the woven dacron is about three orders of magnitude stiffer than knit Chromel-R. The significance of this difference on antenna performance is that the softer knit mesh is less sensitive to thermally induced surface distortions. This can be seen by comparing the performance analysis on the ATS-6 9-m diameter antenna using woven dacron and the knitted Chromel-R mesh material (fig. 25; ref. 14).

The design selected for development for the offset antenna hub structure is based on the utilization of the axisymmetric configuration. The offset wrap-rib will use the radial rib system attached to a central hub as in the axisymmetric design except that the hub is now located in the center of the offset section with the plane of the hub parallel to the local slope of the section. This approach will accommodate the use of a slightly modified axisymmetric hub design. Multiple rib tooling will be necessary to contour the ribs due to the reduction in symmetry, but the proposed configuration will result in ribs of approximately the same length and cross section.

The most significant deviation between the axisymmetric and offset configuration is the deployable feed support structure. The offset antenna utilizes a deployable cantilever feed support configuration. The requirements for the design of this structure will be dictated by the dimensional stability needed to accommodate RF operation commensurate with antenna surface quality. Additionally, the mechanical packaging efficiency of this deployable boom will have to complement the antenna structure so that the complete antenna system can be accommodated by the STS payload compartment. The development for this feed support structure will be unique with respect to the three member trusses usually used on the axisymmetric antenna. New configurations, composite material with dimensional and thermal stability, nonbacklash mechanical joints, and, possibly, active position control will be required by the feed support structure to exploit the optimum RF operation from the basic wrap-rib antenna concept.

The development of the offset wrap-rib concept will be based on an iterative approach of analytical performance prediction which will be followed by model verification using test results from components, scale models, breadboard models, and, ultimately, space flight experiments.

5.2 Technology for Maypole (Hoop/Column)

5.2.1 Summary

As described earlier, the maypole (hoop/column) concept (fig. 7) is a cable-stiffened hoop/column structure that supports an antenna mesh surface. An attractive feature associated with this concept is that the antenna mesh can be shaped to approximate a flat, conical, parabolic, or spherical surface depending upon the application. The maypole (hoop/column) was developed to a feasibility level during the AAFE program, but now more detailed designs and analytical activities (coupled with hardware verification tests) are required through the LSST program. After completing the design verification test through LSST, it would be possible to evaluate this concept through meaningful trade-off studies. Recognizing the fact that smaller deployable designs do not adequately identify problems associated with large antennas, technology development efforts must be focused on resolving: (a) the size limitation of deployable antennas, (b) the point where design transition would be required as the antenna size increases, (c) whether or not ground testing of a large antenna is possible, and (d) the cost effectiveness of the overall design.

5.2.2 Technology Development

The basic technology development approach is to select a "full scale" antenna point design, where "full scale" implies an antenna size (approximately 100 m in diameter) which will address the upper range of antenna applications. A downward extrapolation of the design and performance characteristics shall be made over the range of diameters initially identified. Design verification will be established through subscale and intermediate-scale components of the full-scale "point" design. A 5-m subscale model has been proposed so that concept comparison can be made directly with the TDRSS state of the art techniques and capability. The subscale, 5-m model will be utilized to verify:

1. Control accuracy and repeatability

2. Deployment kinematics

3. Capability and limitation of the design for active surface control

4. Verification of the analysis techniques for performance prediction (including environmental conditions) by correlation of analysis and test results

5. Compatibility of the design with a surface measurement system

6. Preliminary evaluation of the manufacturing and test philosophy/technique developed for the full-scale antenna

The technology development for the maypole (hoop/column) will include an assessment of loads generated by the STS as well as the different types of orbital transfer boosters. Materials used in the maypole (hoop/column) design must be capable of withstanding the orbital temperatures and radiation environment expected during a typical mission. The orbital temperatures could vary from 430°C to -250°C depending on the sun angle and the resulting shading effects during orbit. Specific technology tasks in the materials development area have been included in the LSST Program in support of the maypole (hoop/column) activity.

Due to the nonlinear behavior of some of the performance parameters with size, the validity of all scaling relationships must be verified. Also, the manufacturing techniques will differ for the larger sizes. But still, the use of a subscale model is mandatory in developing the overall technology plan associated with this concept. Some limited fabrication and verification testing of intermediate-scale and full-scale components is included in the program. This effort shall indicate the scaling relationship and performance projections for the full-scale hardware. Also, the economic model and manufacturing and testing technique will be validated using these components.

The projected performance of the maypole (hoop/column) antenna concept could also be nonlinear with the larger sizes. So the analytical modeling capabilities in all areas (structural, thermal, dynamic, and RF) will be developed to include the material and geometric nonlinear effects. In order to project

the performance of a 100-m antenna with an acceptable risk, it is believed that the analysis and test correlation associated with the subscale models, intermediate-scale and full-scale components will prove to be very effective.

In parallel with the preliminary design will be the development of the manufacturing and testing philosophy related to the antenna concept. The size of available test facilities will play a substantial role in selecting hardware dimensions. It is anticipated that extensive ground tests will be required before a possible flight experiment can be suggested. Therefore, the identification of test facilities will be an important activity during the development of the maypole (hoop/column) design.

Finally, through these activities of design, manufacturing, and testing, data shall be obtained for the confident extrapolation of the performance and cost of the maypole (hoop/column) over the complete range of diameters and applications identified through the LSST Program.

6. CONCLUSION

The space system designs evolving through LSST to meet the user requirements involve large space antenna concepts. Preliminary study and results indicate that the technology for concepts and designs must be developed if we are to meet the technological challenges of the future. Achieving an acceptable system performance will depend on a complete system trade involving material characteristics, manufacturing processes, test limitations and uncertainties, predictive analysis capability, and dynamic/structural/thermal/control interaction understanding for the life of the space mission. To exploit the best features of each concept, technological improvements in each area must be addressed and accomplished.

The LSST Program is sponsoring the development of technology related to the two concepts described herein. The basic technology development sequence will consist of analysis, breadboard testing, environmental tests, and predictive analysis for performance projection. Expected results will include:

1. Development and verification of offset wrap-rib and maypole (hoop/column) antenna concepts.

2. Development and verification of predictive analysis methods for the deployable mesh antennas under development.

3. Development of surface adjustment techniques for deployable mesh antennas under development.

4. Test and evaluation of breadboard models, scaled models, and components for concept verification.

5. Development of electromagnetic analysis methods for large space antennas.

In-space testing will most probably be required to complete the verification and validation of the scaling laws and predictive analysis methods developed during the program.

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TABLE I. LSST NEAR-TERM ANTENNA MISSION REQUIREMENTS

Parameter	Communications	Radiometers
Size	30-100 m	10-100 m
Frequency	0.4, 0.8, 2.5 GHz	1-11 GHz
f/d (PARENT)	0.5-1	1-2
Pointing Accuracy	0.035 deg	0.05-0.025 deg
Beams	100-200	300-1000
Surface Accuracy	4-8 mm	3-10 mm
Feeds	Offset	Offset/On Axis
Beam Isolation	30 dB	--
Orbit	GEO	300-600 km
Resolution	--	1-5 km
Revisit	--	3 days-1 week
Swath Width	--	±30 deg
Power Requirements	5 kW	TBD
Lifetime	10 yr	10 yr

TABLE II. LSST FAR-TERM ANTENNA MISSION CANDIDATES

Applications	Frequency GHz	Diameter m	Beams	Pointing Accuracy (System)	Pointing Stability (System)	Orbit km	Surface Accuracy
OSTA	20-30	10-30	100	Pilot Beacon	0.1 deg	GEO	λ/50
Submillimeter	300-1000	10-30	1	0.1 $\overline{\text{sec}}$	0.1 λ/d	400	λ/50
Very Long Based Inferometer	1.4-14 (22)	15-75	1	0.01 deg	±0.01 deg	400-800	λ/10
Atmospheric Gravity Wave Antenna	N/A	100	N/A	5 deg	±0.5 deg	≥250	N/A
Pinhole Camera	N/A	Mask: 20 Boom: 1000		10 $\overline{\text{sec}}$	TBD	400	N/A
Orbital Deep Space Relay Station	30	30	1	1 $\overline{\text{sec}}$	±1 $\overline{\text{sec}}$	GEO	λ/30

Fig.1 Advanced sunflower precision antenna concept

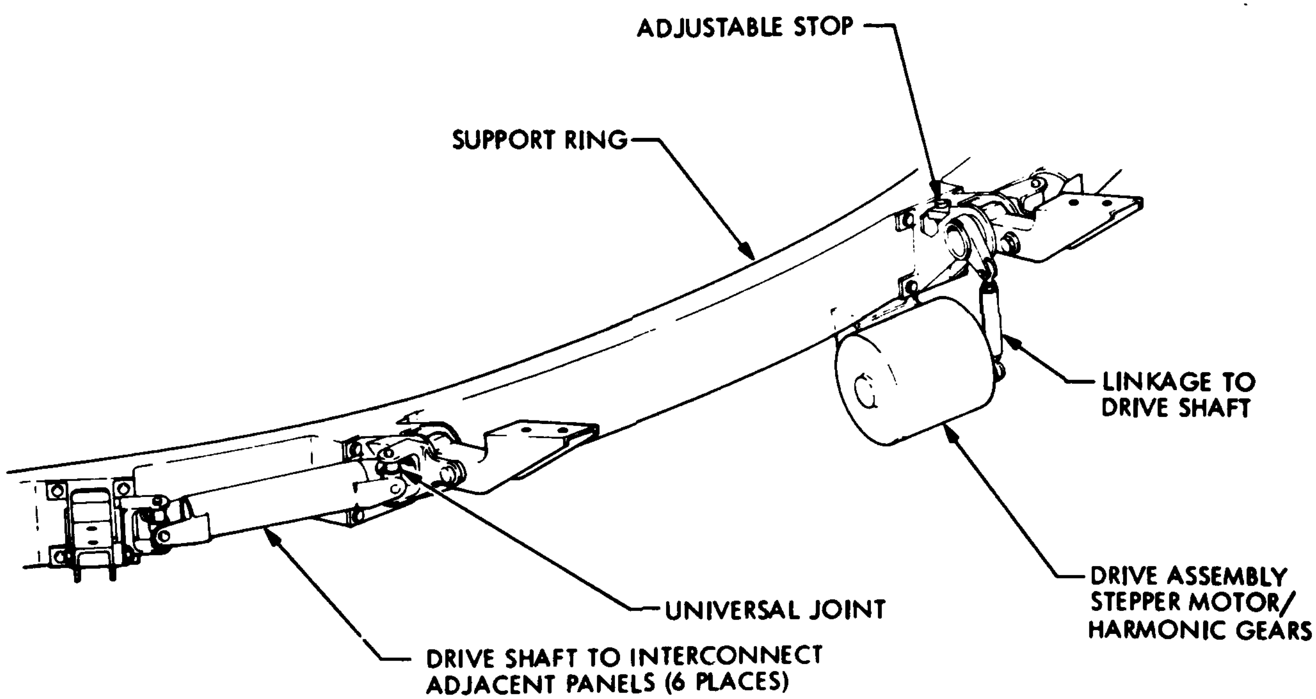


Fig.2 Advanced sunflower precision antenna deployment coupling elements

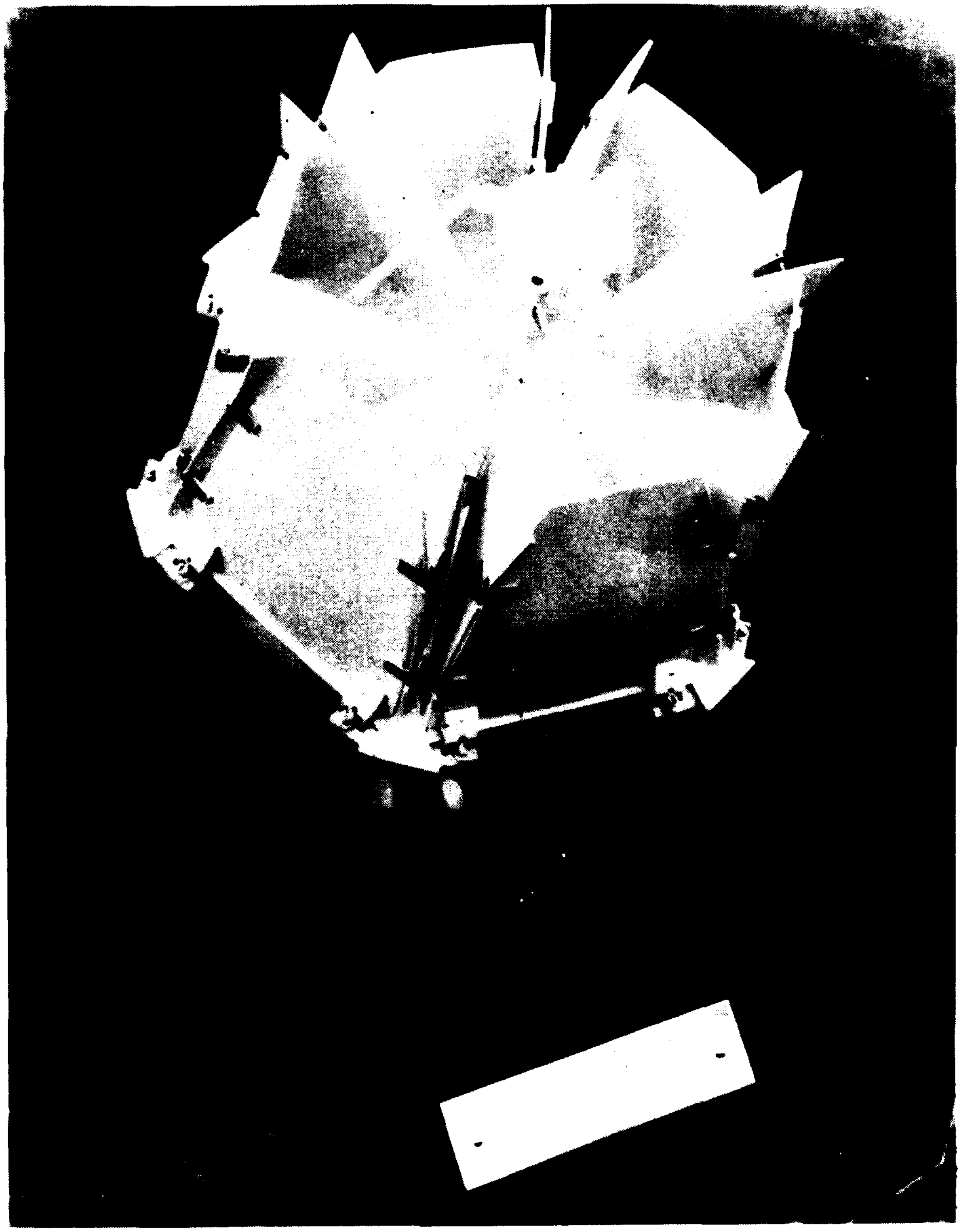


Fig.3 Advanced sunflower precision antenna stowed configuration

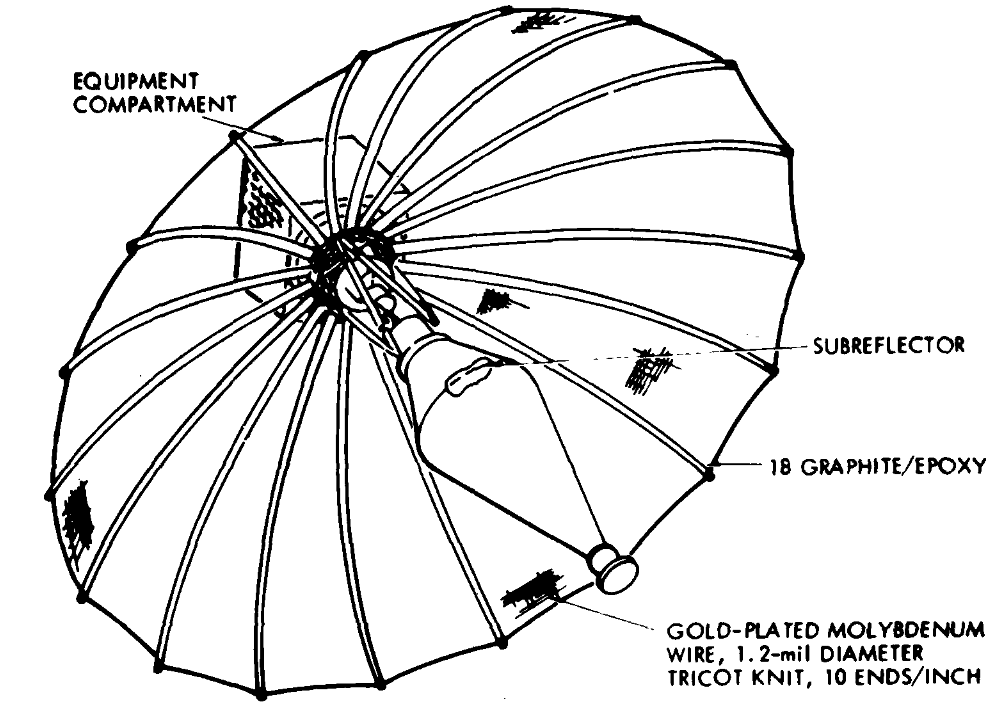


Fig.4 TDRSS antenna concept

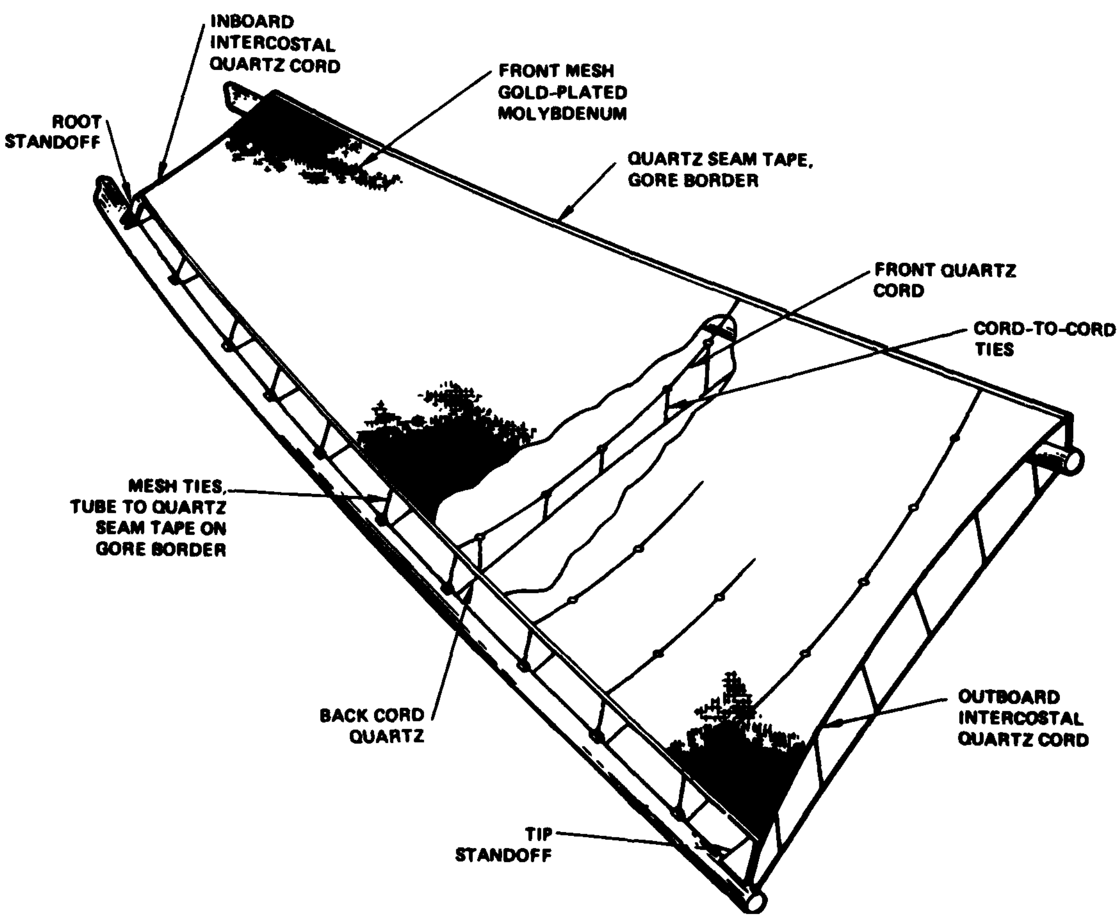


Fig.5 TDRSS secondary drawing surface technique

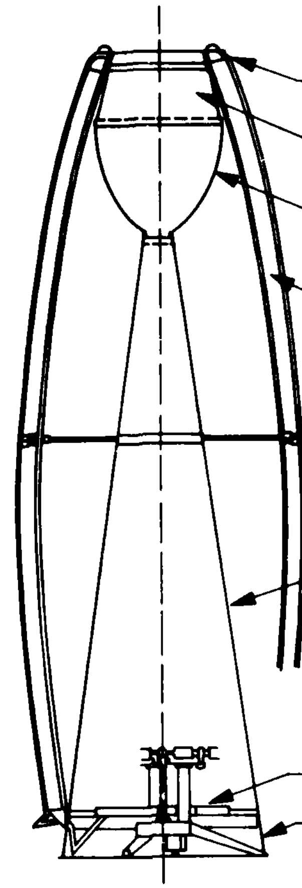


Fig.6 TDRSS stowed configuration and feed support structure

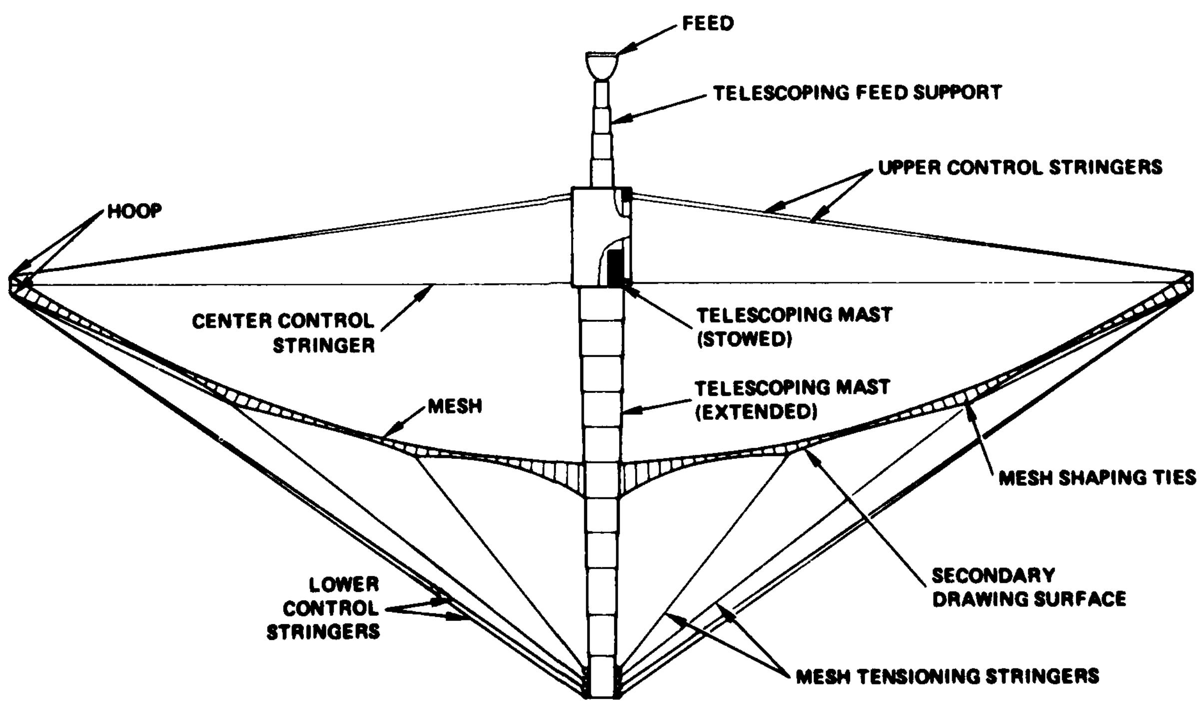


Fig.7 Maypole (hoop/column) antenna concept

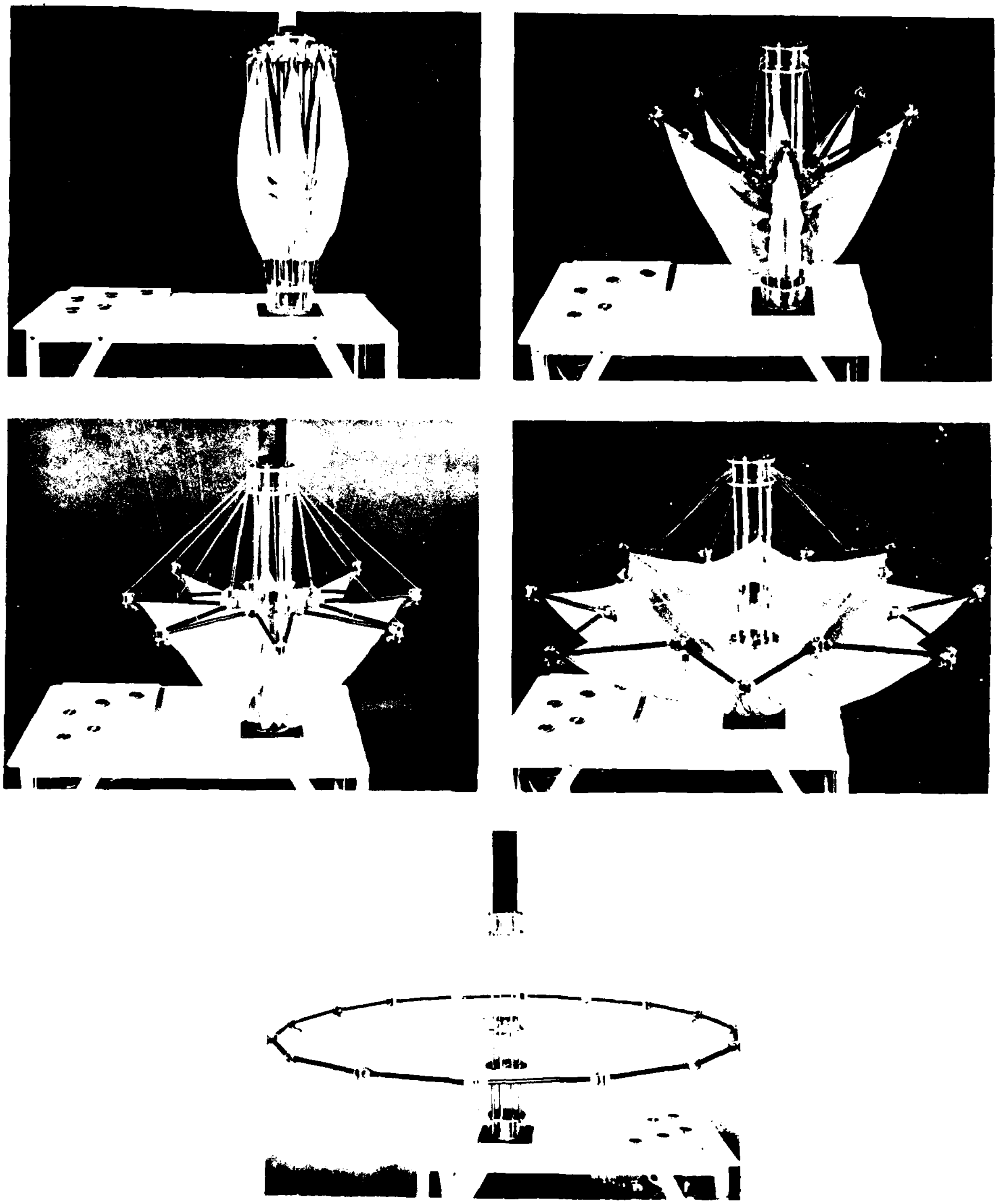


Fig.8 Maypole (hoop/column) demonstration model

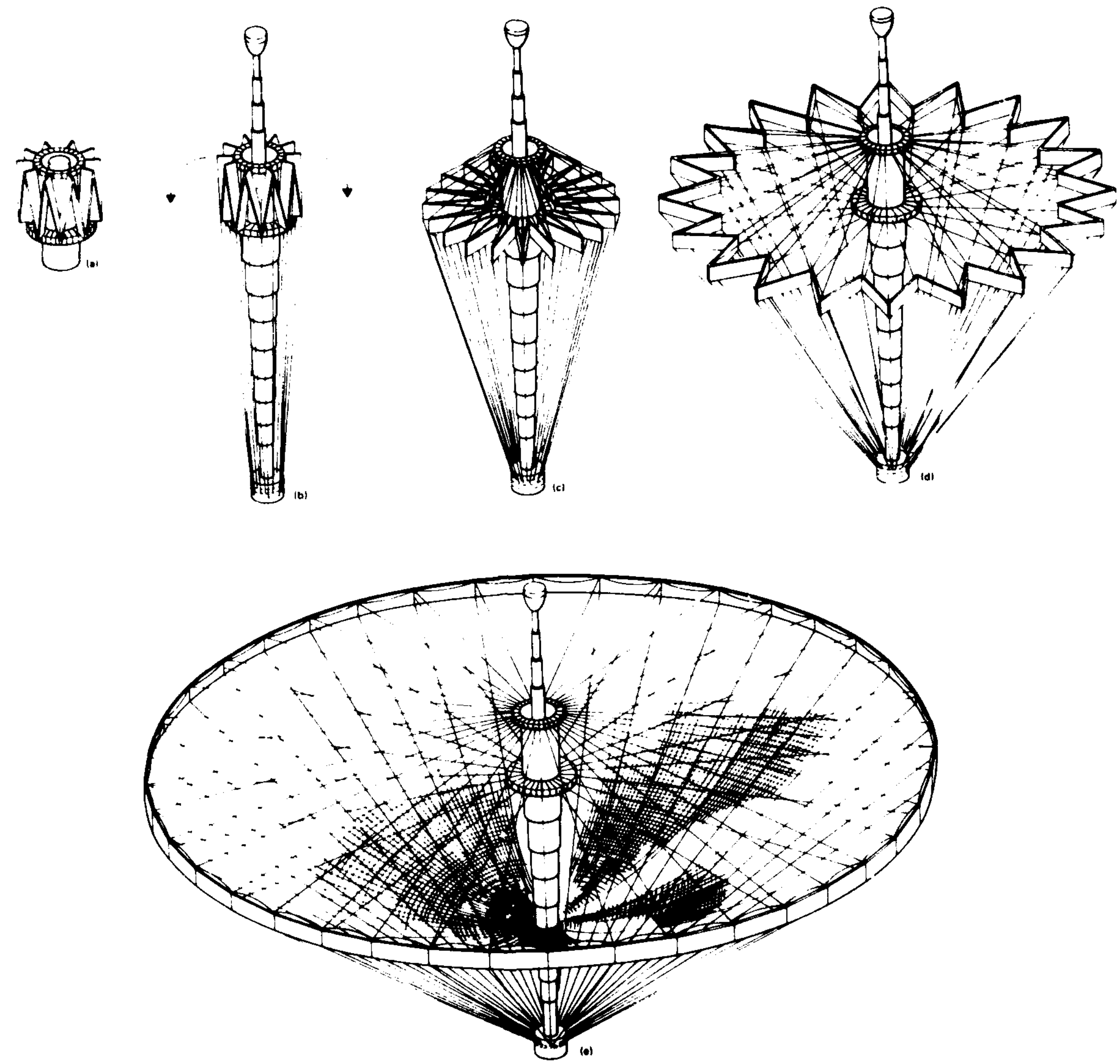


Fig.9 Maypole (hoop/column) deployment sequence

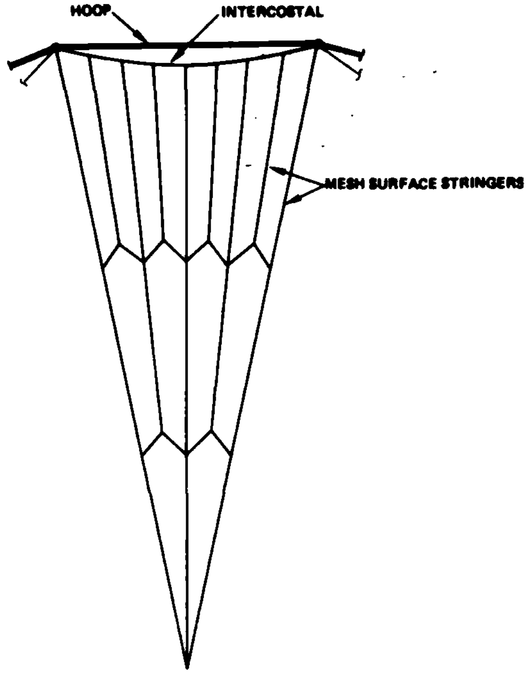


Fig.10 Maypole (hoop/column) mesh surface stringer configuration

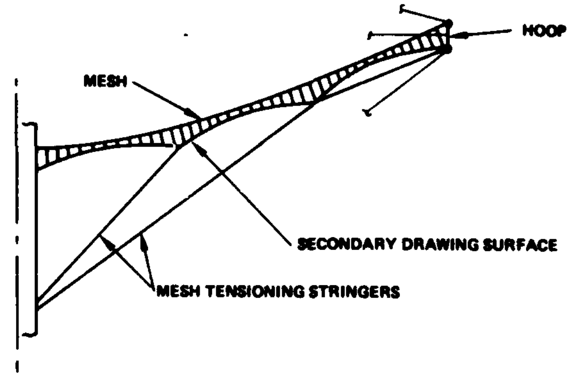


Fig.11 Maypole (hoop/column) shaping technique

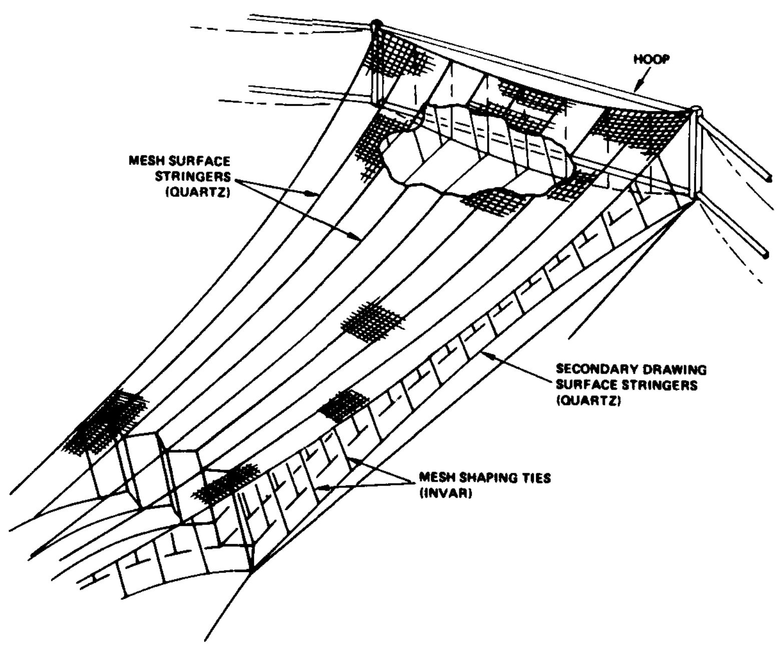


Fig.12 Maypole (hoop/column) shaping configuration

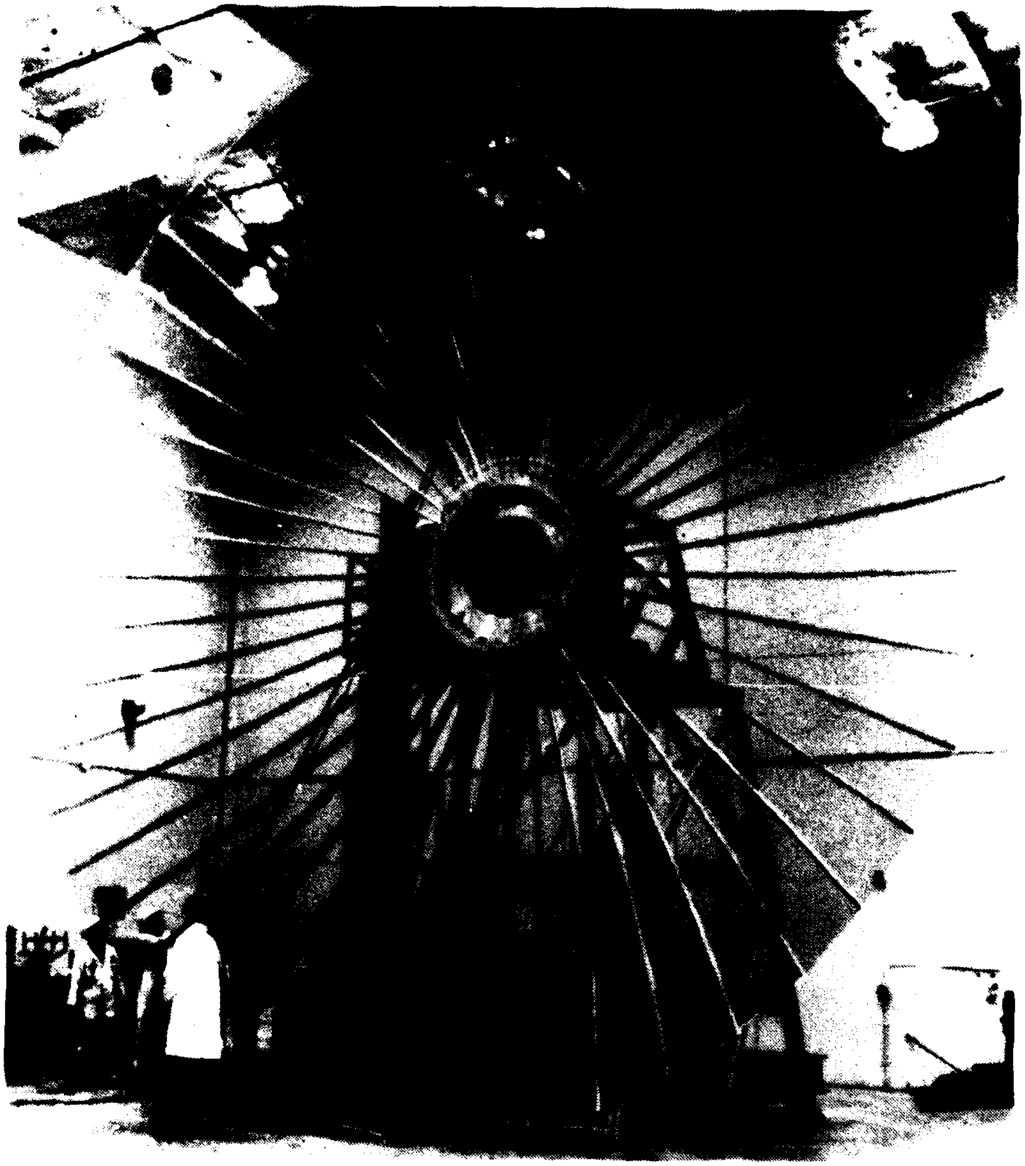


Fig.13   ATS-6 flight antenna

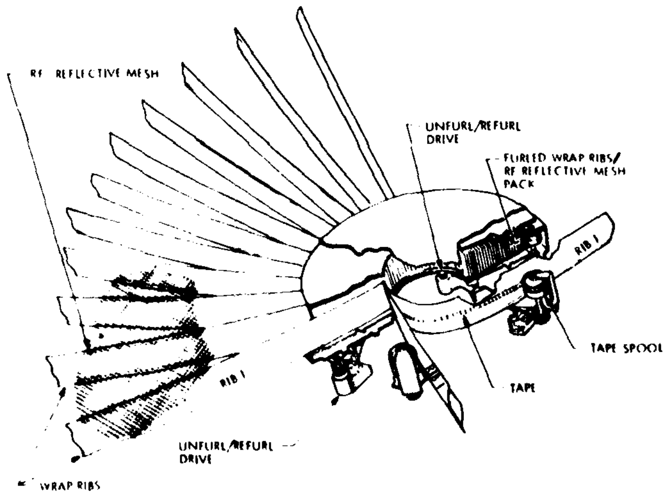


Fig.14   Wrap-rib antenna deployment mechanism

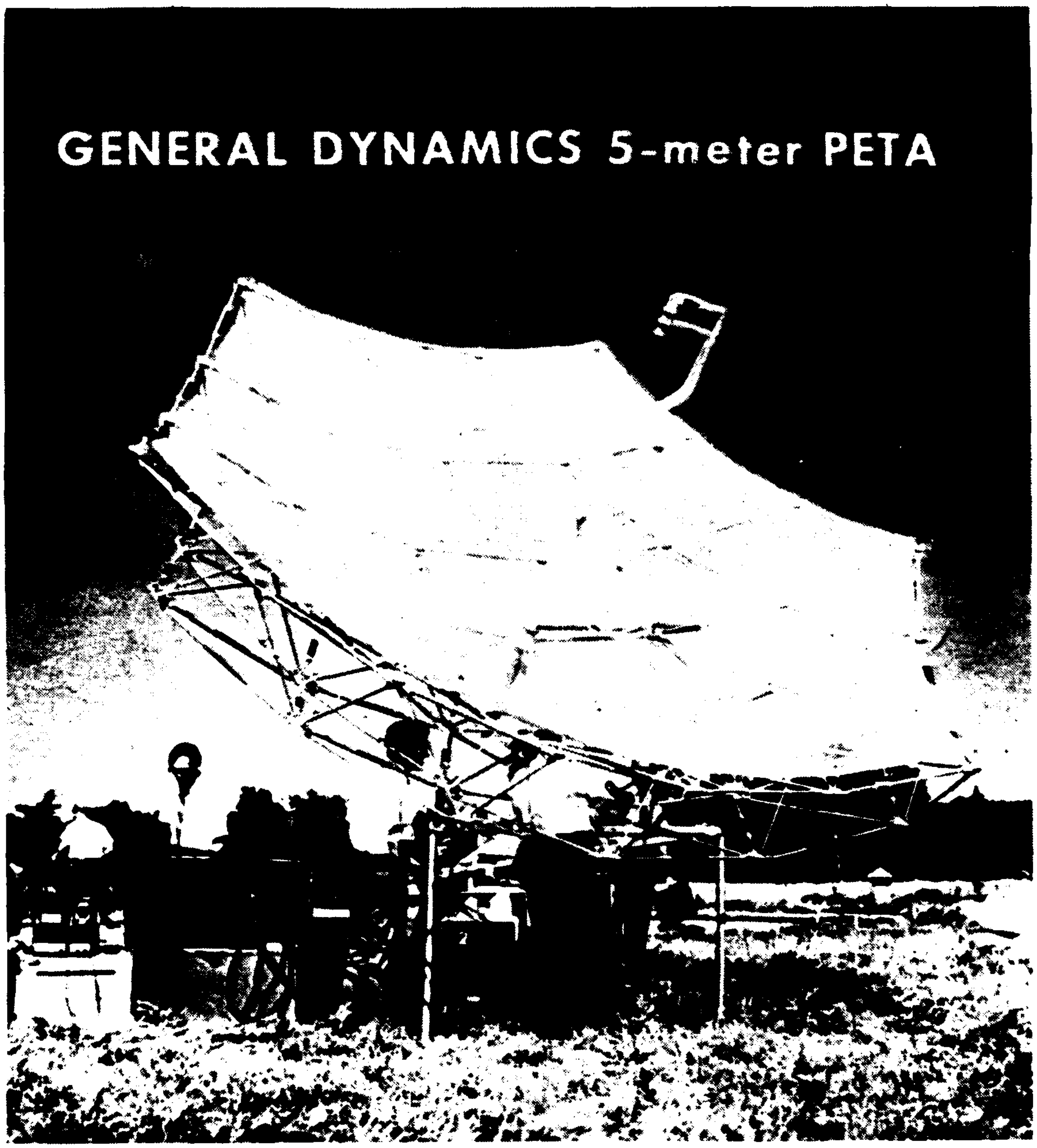


Fig.15 PETA 5-m antenna concept

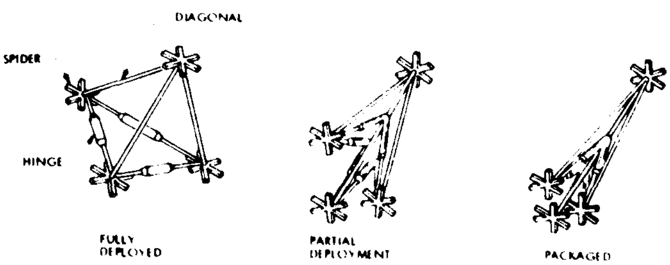


Fig.16 PETA antenna tetrahedron truss

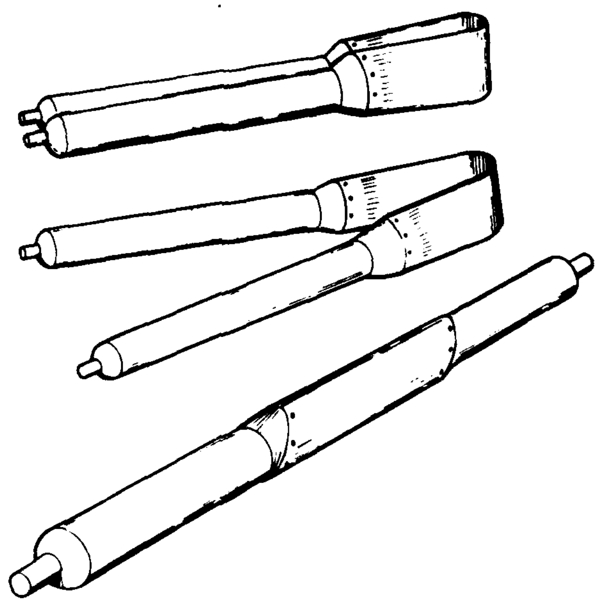


Fig.17 PETA antenna carpenter tape hinge

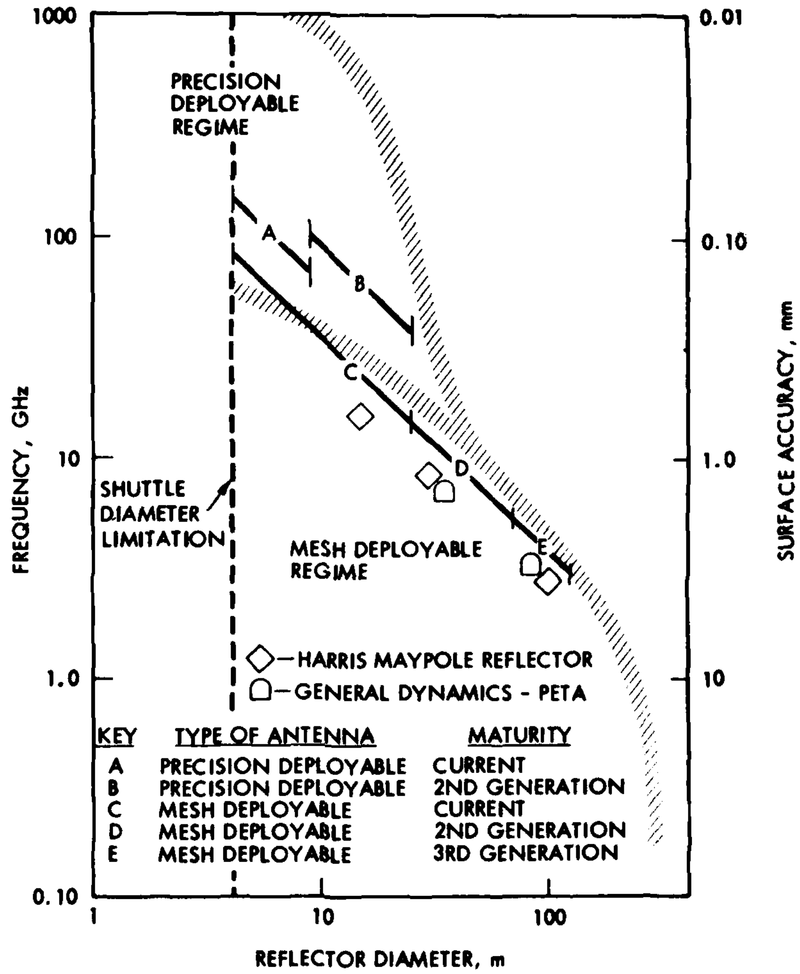


Fig.18 Projected performance for deployable antennas

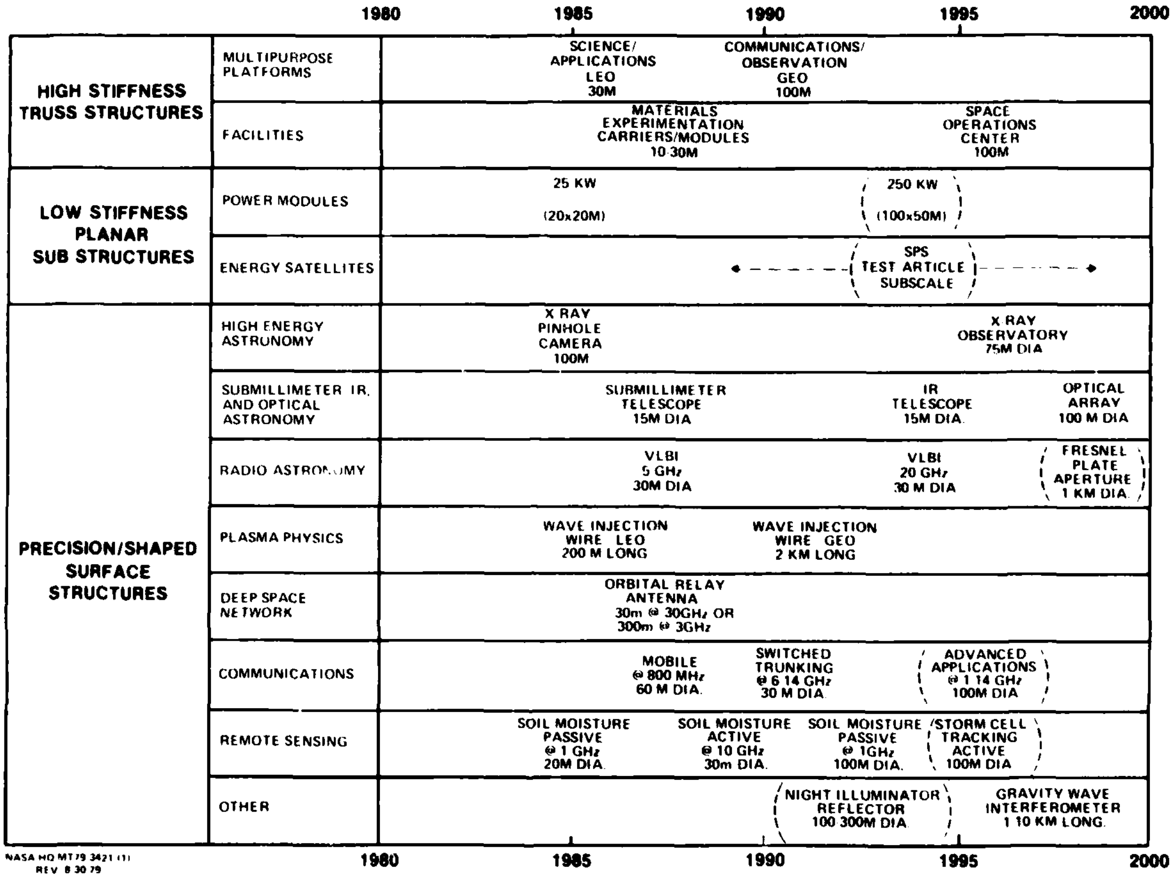


Fig.19 Potential space missions requiring large space structures

Fig.20 Offset wrap-rib antenna concept

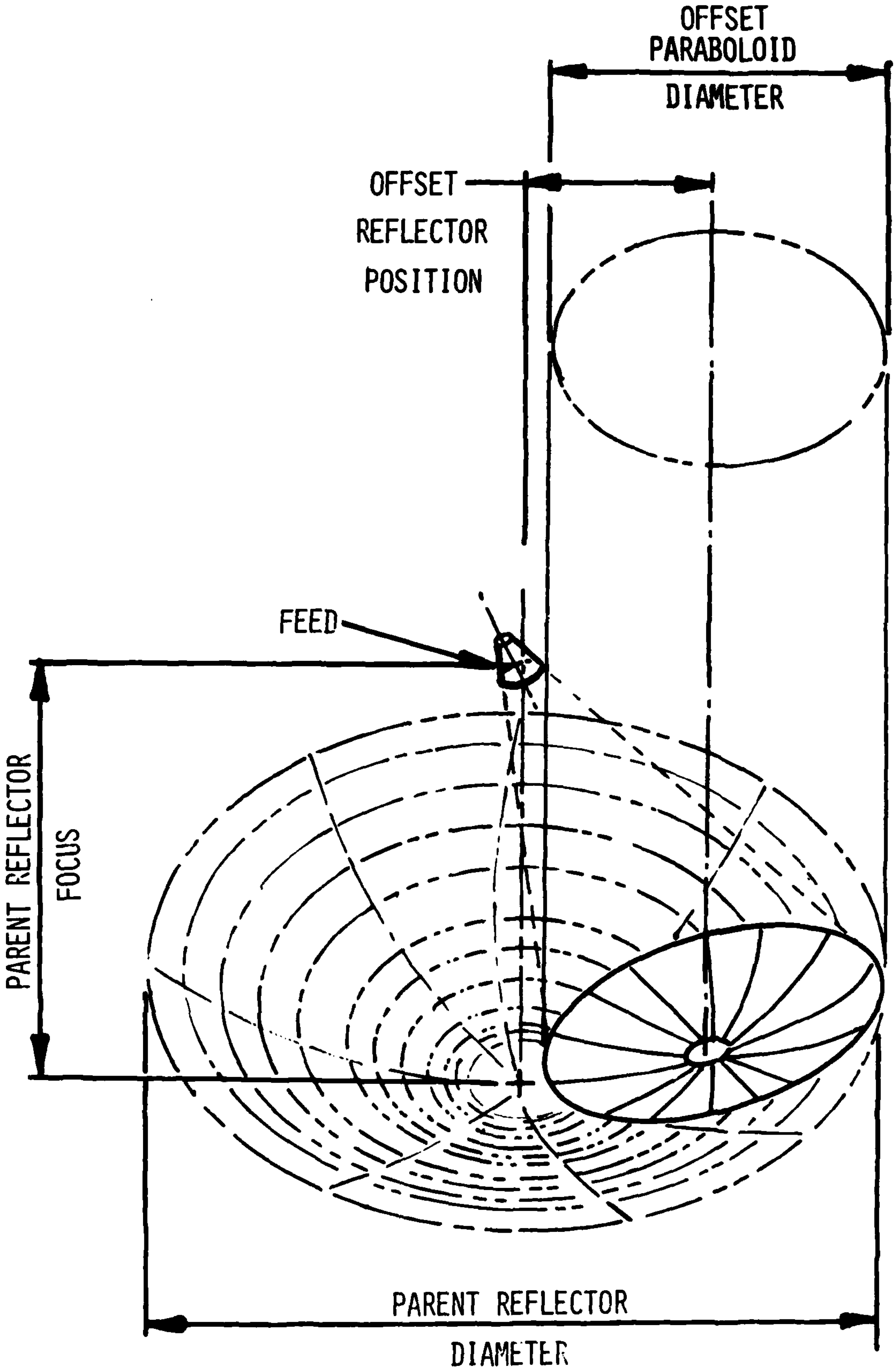
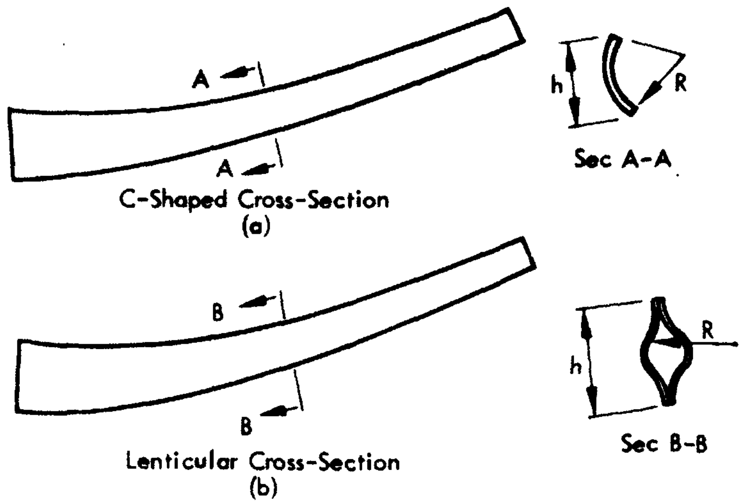
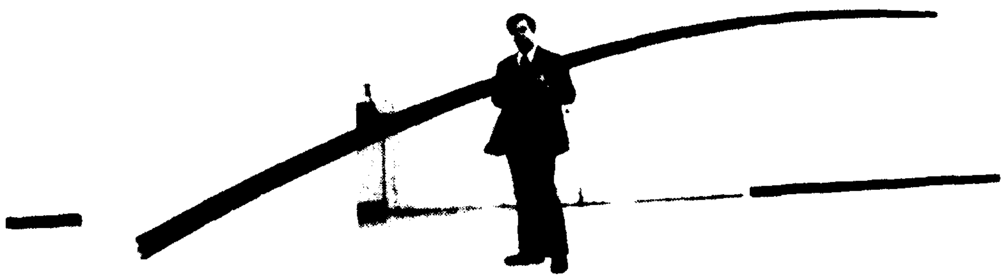


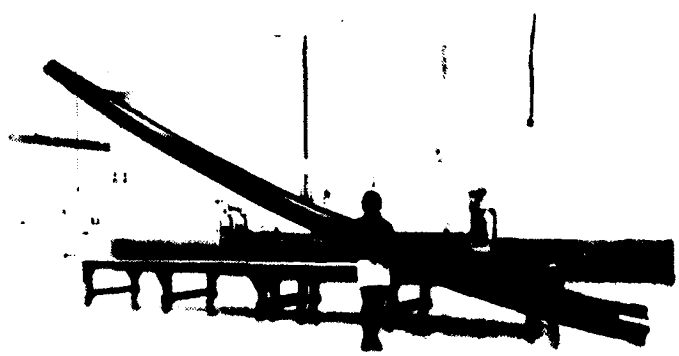
Fig.21 Offset wrap-rib antenna geometry



Antenna Rib Design Configurations



C-Rib of Gr/E for 50-Foot Parabolic Antenna



Lenticular Rib of Gr/E for 50-Foot Parabolic Antenna

Fig.22 Ribs of Gr/E for 50-ft. antenna

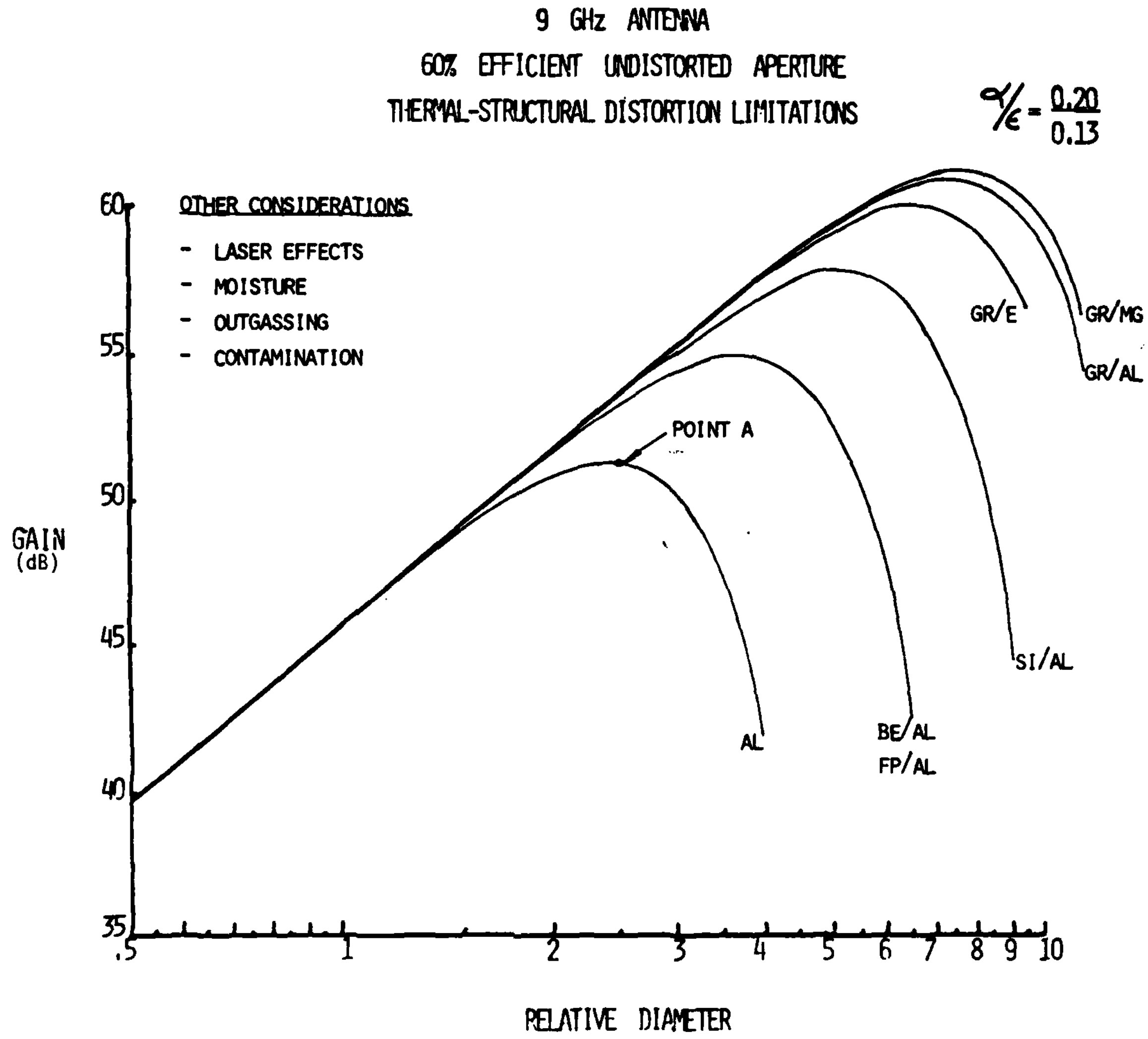


Fig.23 Material effects on performance of a 9 Ghz antenna

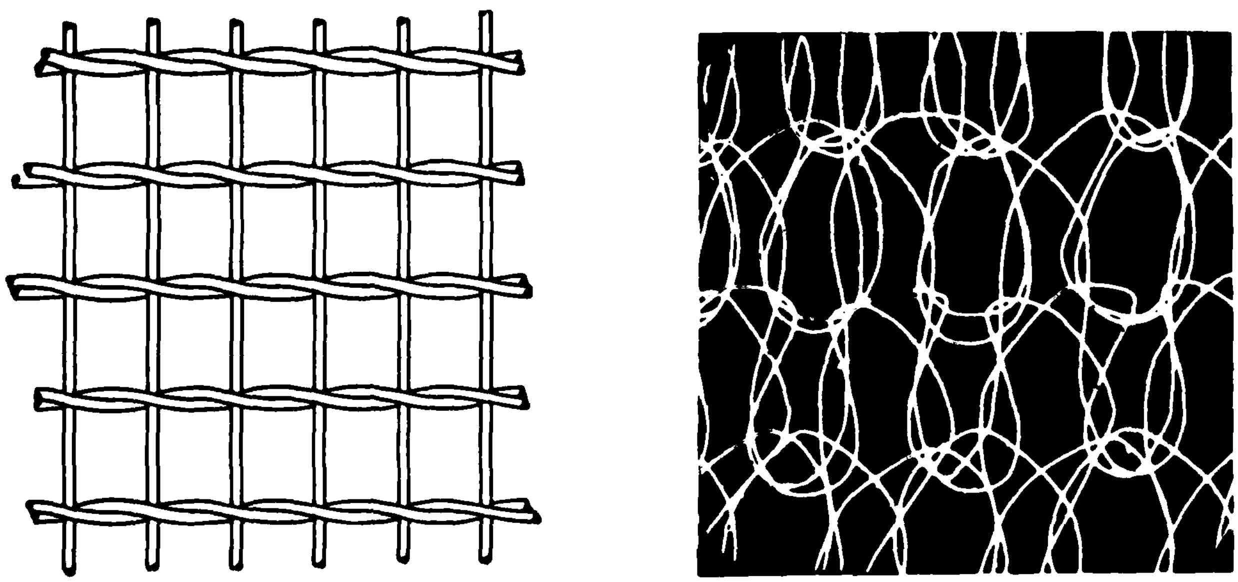


Fig.24 Typical antenna mesh configurations

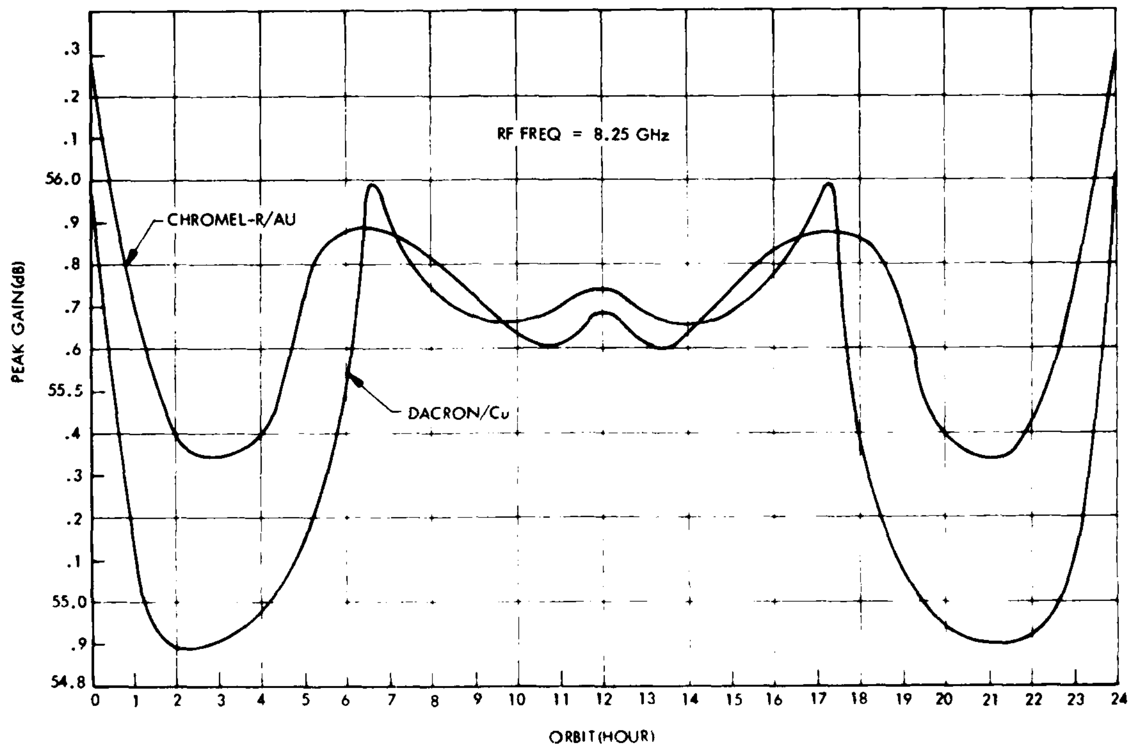


Fig.25 Mesh material effects on performance of ATS-6 antenna

TYPICAL EXAMPLES OF EUROPEAN TECHNOLOGY FOR HIGH STABILITY SPACE STRUCTURES

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SUMMARY

Two contrasting, primary areas of application of highly undeformable space structures are identified to illustrate the state of the art in the European space industry. The technologies associated with the structures of high gain antennas and space telescopes are illustrated by selected examples. The philosophies adopted in translating the electrical or optical requirements initially into mechanical and thermal designs, and subsequently into hardware, are presented. Attention is given to deformations induced by launch and on-station environments, to methods of controlling local environments, and to demands from terrestial assembly and integration. In addition to existing designs and hardware, current trends and developments are identified.

INTRODUCTION

With the demand for higher performance from both communication and scientific satellites, the designs of a number of key structural components have become by necessity more sophisticated. In terms of dimensional accuracy and stability, this is particularly evident in antenna and telescope applications. It is these two principal areas that are used in the following paragraphs to illustrate the capabilities of the European space industry in this field of highly undeformable structural design. However, it should be recognised that the technologies described may be equally relevant to other equipments, from the local detail design of solar array panels to the design of modules for large space structures.

HIGH GAIN ANTENNAS

Prior to reviewing the high performance antennas currently available within Europe, it is appropriate to identify those factors to be considered by the mechanical design of typical spacecraft hardware. The launch environment has perhaps the most significant impact on strength and stiffness, vibration and quasi-static load requirements determining materials, sections and load paths. In-orbit thermal and radiation environments and life requirements generally have less effect. For the high gain antenna this situation is not maintained. In addition to constraints of mass, stiffness and strength, the wavelengths at which high gain antenna are being required to operate are becoming shorter. High dimensional stability is becoming an even greater premium. Consequently in-orbit thermal deformations due to transient temperature distributions and to stress relieving or ageing are of particular importance, playing a major rôle in the selection of materials and methods of mounting. Similarly the effects of ultra-violet radiation and absorption of water have to be considered. In addition, it is necessary to give particular attention to production techniques and to control response to launch thus minimising resultant permanent deformations.

The significance of any of these potential disturbance factors will vary in accordance with the electrical design requirements and their interpretation into a mechanical and thermal design and configuration. To assess their significance for any specific application is not, unfortunately, so simple. Whilst it is practical to verify the acceptability of any permanent distortions and deviations resulting from manufacture and integration and from launch by a combination of simulated testing and inspection, the measurement of movements arising from in-orbit thermal conditions cannot currently be performed to the necessary accuracies. Using photogrammetric test techniques at present available to the European Space Agency (ESA), distortions under solar simulation conditions can be determined to an accuracy of nominally 0.3 mm. Predicted movement at the rim of a 1 metre diameter carbon fibre composite reflector at -180°C is itself of the order of 0.5 mm! To directly determine the electrical performance of an antenna whilst subject to the constraints of a solar simulation test facility is not practical. Yet, experience has shown that it is the in-orbit distortions that have the largest potential contribution to the degradation of performance. Consequently, particular emphasis is placed on careful design analyses and on attempts to minimise these transient and permanent thermal deformations.

The most marked gains in dimensional stability can be achieved in the selection of material. As demands on RF (radio frequency) performance have increased, requiring structures of greater stability, fibre reinforced composites have exclusively replaced aluminium alloy as the primary material for antenna reflectors. The more advanced antennas have utilised carbon fibre reinforced plastics (cfrp). Whilst others have employed glass fibre (grp). Both materials have also been used for antenna feed supports. Tables 1 and 2 present a summary of some existing and proposed antennas.

Employing technology previously used on the OTS satellite now in operation, the ECS Spot Beam and Eurobeam Antennas include reflectors fabricated from grp faceskins bonded to aluminium honeycomb core. Compared to subsequent antenna of cfrp construction, these units are smaller and less demanding of dimensional stability. Displacements at the reflector rim (Fig. 1) are of a similar magnitude to those experienced by the Intelsat V cfrp reflectors of twice the diameter. In addition, it has been shown to be necessary to include an artificial thermal ageing procedure as a part of the production sequence, prior to integration and alignment with the spacecraft, thus minimising degradation in orbit. After 25 cycles in vacuum between the extreme temperature limits, no further significant permanent deformation occurs, ageing following an exponential decay.

Like the ECS antennas, the Intelsat V East and West Spot Beam Antennas (Fig. 2) provide regional coverage. However, due to the nature of the circular polarisation of the RF signal and the off-set feed geometry increasing the sensitivity to cross-polar effects, a greater dimensional accuracy and stability is required. The beamwidth is also considerably narrower. To overcome the disadvantages of grp, preference is given to the adoption of cfrp. By combination of the subsequent low coefficient of thermal expansion with the development of processing techniques to reduce internal stresses, the degradation due to thermal ageing becomes almost negligible whilst transient thermal distortions are diminished. Table 3 presents data describing the deviations to surface geometry of an Intelsat V flight reflector. The contributions from manufacture, simulated launch and predicted in-orbit thermal transients are each indicated. Table 4 indicates the effect of thermal cycling, no significant ageing occurs, the differences in values being attributable to the method of measurement.

In contrast to the preceding examples, the MARECS L-Band antenna offers global coverage. Having a considerably greater beamwidth a lower pointing accuracy can be tolerated. Although operating at a lower frequency, the shaped beam, designed to distribute more power to the edge of coverage, still requires a high degree of dimensional stability, necessitating the use of cfrp. Peak distortions are sufficient to define the allowable deformability, no rms requirements for the reflector or feed movements are specified since the longer wavelength can accommodate general production practice.

Of the forthcoming antenna, the most imminent is that for the scientific satellite ISPM, International Solar Polar Mission. The construction and dimensional stability requirements of the reflector are expected to be similar to those achieved with the Intelsat V Spot Beam hardware. Although having a similar beamwidth, the pointing accuracy is more severe since the mission takes the spacecraft to Jupiter rather than an Earth orbit. Preliminary studies have indicated that feed movement and antenna alignment can be sufficiently constrained by the use of cfrp tubular struts and ties.

Returning to telecommunication applications, design studies of direct TV broadcast satellite systems have shown a need for reflectors of between 3 and 4 metres diameter, larger than existing European hardware. The RF signal requires high power in the main beam with very low sidelobes to minimise interference with broadcast signals of neighbouring regions. The signal is highly directional, demanding a narrow beamwidth and accurate pointing. The electrical design thus generates stability and geometry requirements of a greater severity than previously experienced. However, by the introduction of RF sensing, whereby the antenna itself provides the signal to maintain the correct attitude, the impact is partially relieved. Typical configurations are illustrated by Fig. 3, the reflector being mounted on an antenna pointing mechanism (APM).

National inter-city communication antenna systems are still more directional than those for direct TV broadcast. The beamwidth is exceptionally narrow although the sidelobe constraint is less severe. Operating at higher frequencies, the performance is particularly sensitive to reflector surface deviations. However, RF sensing would again be employed, allowing dimensional stability to be of a similar order to the previous application. The type of construction remains to be determined. Dependant upon size, nominally 4 metres diameter, launch vehicle envelope and spacecraft configuration, unfurlable antennas may be necessary - a technology not currently available within the European space industry.

An intermediate method of construction is currently undergoing development. The load carrying structure of the reflector is comprised of a framework fabricated from a series of cfrp tube members. This spaceframe in turn supports a fine wire mesh, the size of the grid being a function of the RF wavelength. The dimensional stability and surface accuracy remain to be demonstrated. The spacecraft configuration of Fig. 3b may require such a device if the disturbance torques resulting from solar winds impinging on the reflector are to be minimised.

TELESCOPE STRUCTURES

As with the high gain antenna, the most significant potential disturbance factor for space telescopes is the in-orbit temperature environment. In addition, telescopes are particularly susceptible to deformations arising from assembly and integration. For example, compensation is made for distortions due to the Earth's gravitational field and for temperature differences between setting-up and orbit conditions.

This is more readily appreciated when comparing the dimensional accuracy requirements. Whereas the pointing accuracy of an antenna may be specified in arc minutes, telescopes have to be precise to several arc seconds. Similarly, the focal length of a telescope needs to be controlled to microns rather than millimetres.

The differences in these requirements is reflected in the contrasting methods of mechanical and thermal design. As shown in earlier paragraphs, antennas rely heavily on the physical and mechanical characteristics of fibre reinforced composites. These properties combined with passive means of thermal control, paints and thermal blankets, are sufficient to maintain the necessary dimensional stability. The same philosophy is not necessarily appropriate for telescopes. Aluminium alloys are used extensively, the good thermal conductivity of the metal being used to diminish thermal gradients through the telescope structure. Care is taken in the design of interfaces between the spacecraft and its environment and the telescope to control the flow of heat. In addition, active thermal control systems are combined with the conventional passive means, when required. A summary of a selection of space telescopes is given in Table 5.

The dimensional stability requirements vary with the mission. The approach applied to the thermal design can also be seen to vary. Total reliance on passive means being sufficient in some cases whilst active control, being necessary in other instances.

Both S2/68 and EXUV telescopes rely on passive thermal control of the telescope structure, although the latter does employ heaters to control the temperature of the mirrors. The dimensional stability necessary can be met by careful selection of materials and by detailed attention to the method of mounting the mirrors and detectors. The telescope tube is in each instance fabricated from aluminium alloy sheet adhesive bonded to aluminium honeycomb core to form a sandwich construction. By choosing aluminium for the tube differential expansion between the tube and the mirrors becomes negligible, aluminium also being used for mirror construction.

To meet the more stringent requirements of the International X-Ray Explorer telescope, IXE, (Fig. 4) using a similar method of construction alone is not sufficient. An active thermal control system was designed and a representative telescope tube was subjected to test. The control system employed electrical heater elements arranged around the tube with a number of invar rods running along its length to provide a datum. The demonstration was successful in verifying the feasibility of the system. Indeed, it was found that the heater control loop could maintain the temperature of the tube to within a band of $\pm$ 0.125 deg C of the setting-up temperature. The focal length could be maintained well within the maximum allowable deviation of 20μm.

In contrast the IRAS infra-red telescope employs both conventional means of passive thermal control, namely paint and thermal insulating blankets, and a cryogenic system. The latter controls the temperature of the detectors to that necessary for their functioning and the structure temperature to that required to maintain a low background level. Isolation between the telescope and the spacecraft is achieved by means of a titanium structure and blankets.

As illustrated by these examples, it has been found that, with these basic structural and thermal design techniques, the demands of high dimensional stability imposed by certain applications can be met - without resort to the specialised technology and higher costs of composite materials. The structure of the faint object camera (Fig. 5), now under development as a part of the Large Space Telescope, is an exception, however. The 2 metres optical bench, designed to support the proton detector and mirror assembly, is manufactured from carbon fibre composite in order to achieve the required dimensional stability whilst meeting the imposed mass constraints and permitting line of sight through the structure.

CONCLUSIONS

It is evident that the technologies are available to respond to the high dimensional stability and accuracy requirements of current high gain antenna and telescope designs. Antenna demands have been met by the introduction of high performance materials into the structural design and processing. Telescopes, although requiring a greater degree of undeformability, have been possible without recourse to composites but by controlling their operating environment when necessary.

From a comparison of identified antenna future needs with those of telescopes, the greatest advances may expected to be required by the former. In the more distant future it may become necessary to combine the advantages of composite materials with those of the controlled thermal environment to achieve the required dimensional stabilities. Such a development may be expected to occur as the RF design of antennas advances and when telescopes of higher resolution are required. It is also possible that large space structures, from Orbiting Antenna Farms to Solar Power Stations, will necessitate such a technology.

TABLE 1

Some Existing European Satellite Antenna

Satellite and Antenna	Nominal Dimensions: Reflector Diameter	Nominal Dimensions: Focal Length	RF Characteristics: Freq (GHz)	RF Characteristics: Beam Width	RF Characteristics: Con-fig.	Allowable Distortions	Construction: Reflector	Construction: Feed Support
ECS Spotbeam	0.616	0.253	11	3.7^{o}	centre fed para-boloid	Alignment : 0.1^{o} reflector : - 0.2mm rms manu-facture. - 1mm peak thermal transient	grp faced aluminium honeycomb core	cfrp pultruded struts
INTELSAT-V West Spot Beam	1.12m	1.12m	11/14	1.6^{o}	off-set fed para-boloid	reflector: See Table 3(a)	cfrp faced al. honey-comb core.	space frame tower of cfrp tubes (US supply).
MARECS L-Band	2m	0.602	1.5	18^{o}	centre fed shaped dish	low pointing accuracy; reflector: - 1mm peak at half radius - 2mm peak at rim	cfrp faced al. honey-comb core.	grp tubular struts

TABLE 2

Some Future Antenna Applications

Satellite and Antenna.	Nominal Dimensions: Reflector Diameter	Nominal Dimensions: Focal Length	RF Characteristics: Freq. (GHz)	RF Characteristics: Beamwidth	RF Characteristics: Config.	Allowable Distortions
I S P M High Gain Antenna (Scientific)	1.65m	0.83m	S - Band: 2.1 X - Band: 8.4	S - Band: 6.3^{o} X - Band: 1.6^{o}	Centre dual feed, para-boloid	X-band alignment: 0.05^{o} reflector - similar to I-V West Spot (See Table 3a). Feed: - 0.3mm lateral - 1.0mm axial
Direct TV Broadcast	3 - 4m	-	11-18	0.6^{o} - 1.4^{o}	off-set fed para-boloid or shaped	more severe than ISPM HGA, but uses RF sensing.
National Inter-City	4m	-	20/30	0.25^{o}	to be deter-mined.	more severe than ISPM HGA, but uses RF sensing.

TABLE 3

Summary of Contour Data for Typical I-V West Spot Beam Flight Reflector (Diameter 2R)

SOURCE OF DEFORMATION	RMS mm		Max Deviation (mm)	
	$r \leqslant R/2$	$\frac{R}{2} < r \leqslant R$	at R/2	at R
1. Manufacture	0.058	0.158	0.132	0.453
2. Manufacture + Simulated Launch + 3 Thermal Cycles	0.056	0.161	0.118	0.435
3. In-Orbit Thermal Distortions (Worst Case)	0.059	0.205	0.085	0.350
Accumulative (2 + 3)	$\leqslant$0.115	$\leqslant$0.366	0.203	0.785
Requirement	0.15	0.6	± 0.5	± 1.0

TABLE 4

Effect of Thermal Ageing on Typical I-V West Spot Beam Reflector Profile (Thermal Cycle: -180°C to +100°C at 10^{-5} Torr)

SOURCE OF DEFORMATION	RMS mm	
	$r \leqslant \frac{R}{2}$	$\frac{R}{2} < r \leqslant R$
On completion of Manufacture	0.066	0.171
After 6 Thermal Cycles	0.062	0.135
After 16 Thermal Cycles	0.066	0.154

TABLE 5

Summary of Some Existing and Proposed European Space Telescopes

Telescope	Operative Wave Band	Structure Size (M)		Telescope Dimensions (H)		Thermal Control	Allowable Deformations due to Structure		Launch Date
		Length	Diameter	Focal Length	Aperture		Image arc sec.	Focal length (μm)	
S2/68	U-V	2.0	0.5	1.23	0.30	Passive	12	< 40	1972
IRAS	Infra-red	1.5	0.75	5.5	0.6	Cryogenic - telescope tube: 10-30°K detectors: 2°K.	< 30	~ 150	1981
1XE	X-Ray	2.5	0.77	1.88	0.55	electrical heaters - telescope tube: ± 0.67 deg C variation.	1	< 20	1977 (preliminary design only).
EXUV	X-Ray	2.9	0.8	1.7	0.61	passive plus heaters at mirrors, telescope structure ± 5 dec C variation.	60	< 80 (u-v)	1979 (preliminary study).
	u - v	1.46	0.8	0.72	0.67				

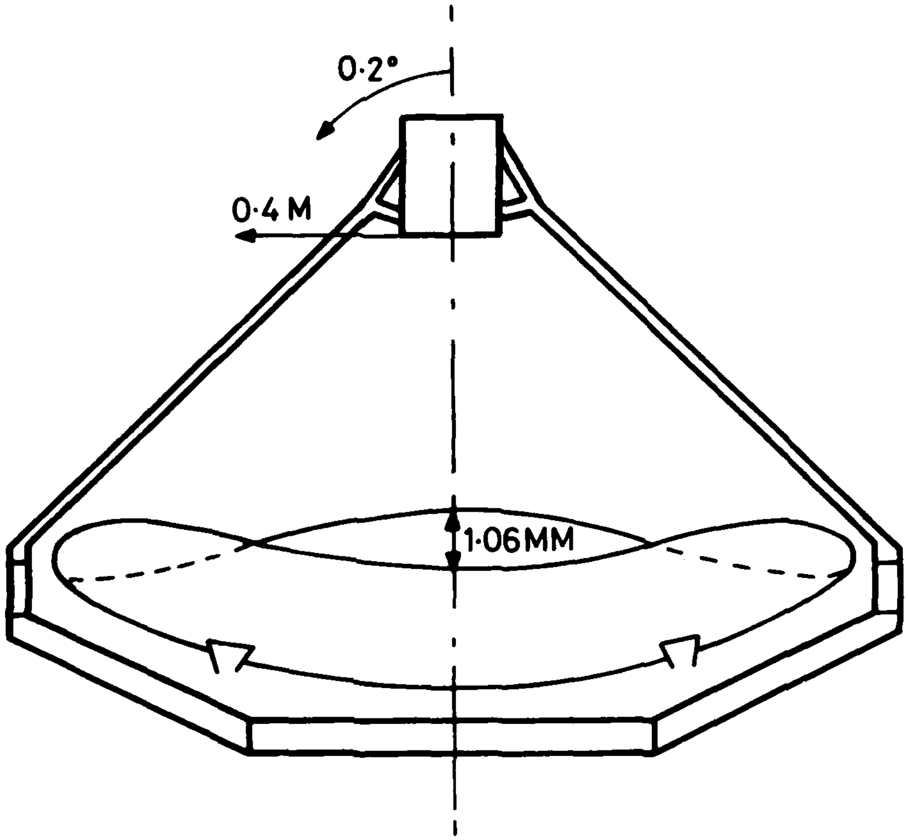
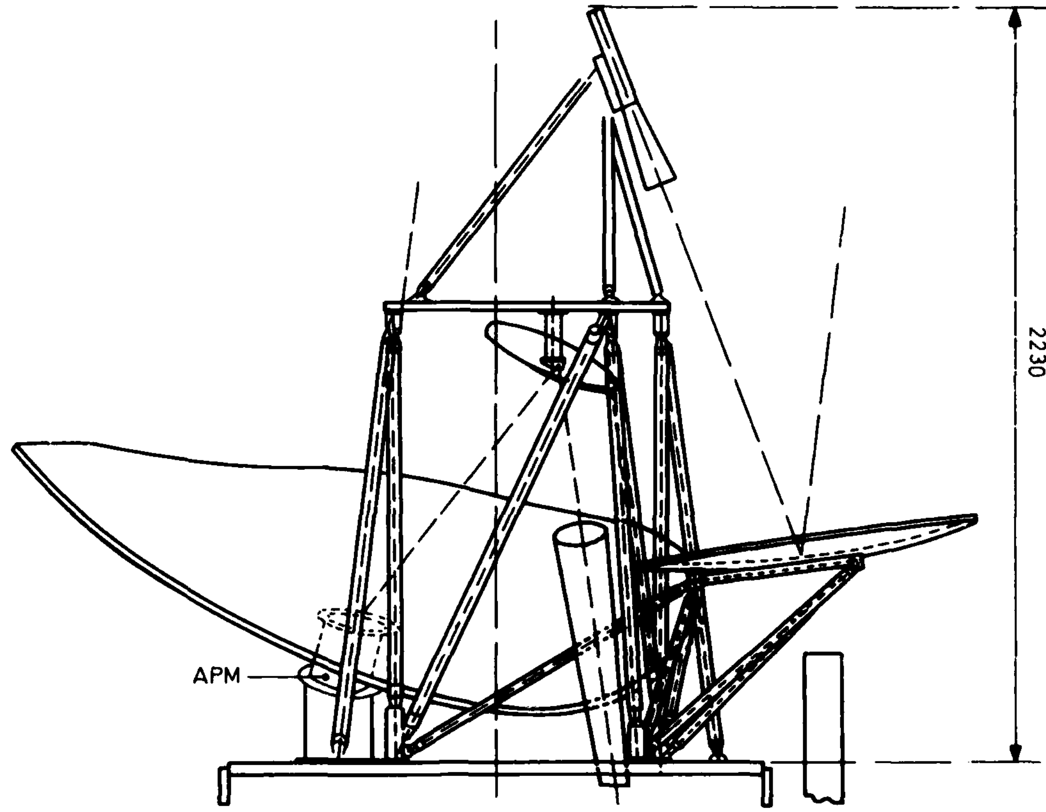


Fig.1 Transient thermal distortions of ECS
spot beam antenna at −165°C

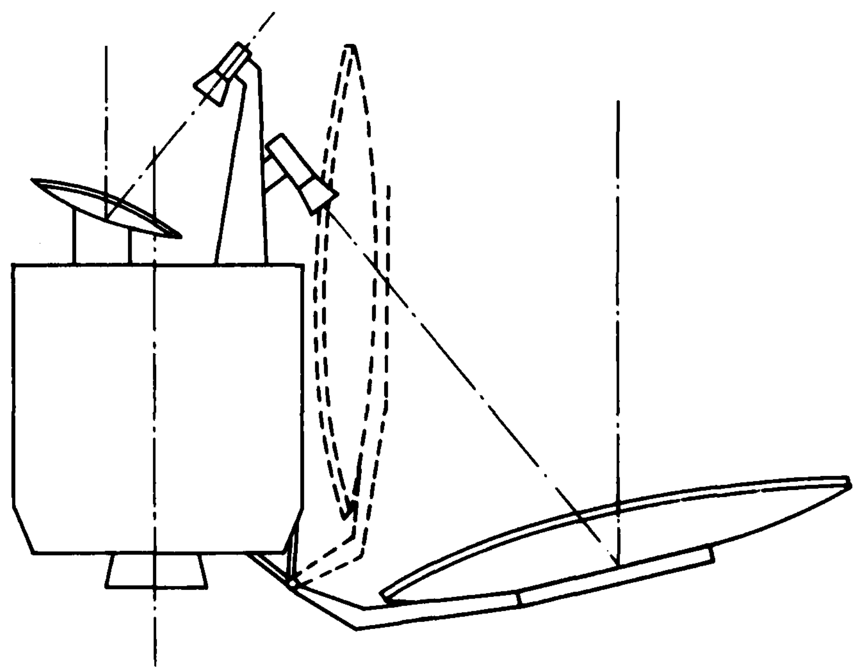
(a) Laying-up of CFRP faceskin

(b) Measurement of surface profile

Fig.2 Intelsat V spot beam reflectors



(a) ANTENNAE MOUNTED ON TOP FLOOR OF SATELLITE



(b) ALTERNATIVE SATELLITE CONFIGURATION WITH LATERALLY DEPLOYED REFLECTOR

Fig.3 Typical direct TV broadcast antenna configurations

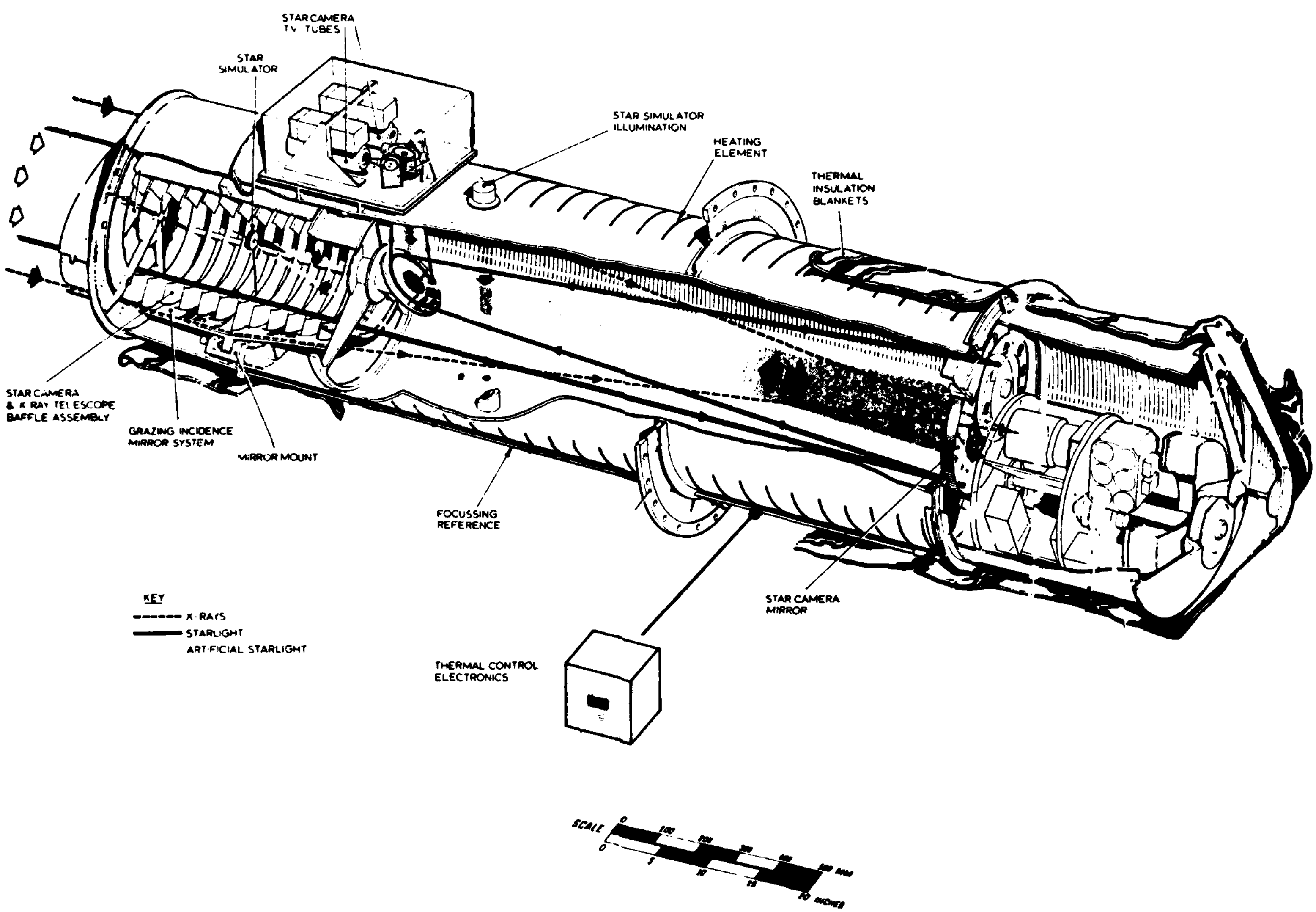


Fig.4 IXE telescope

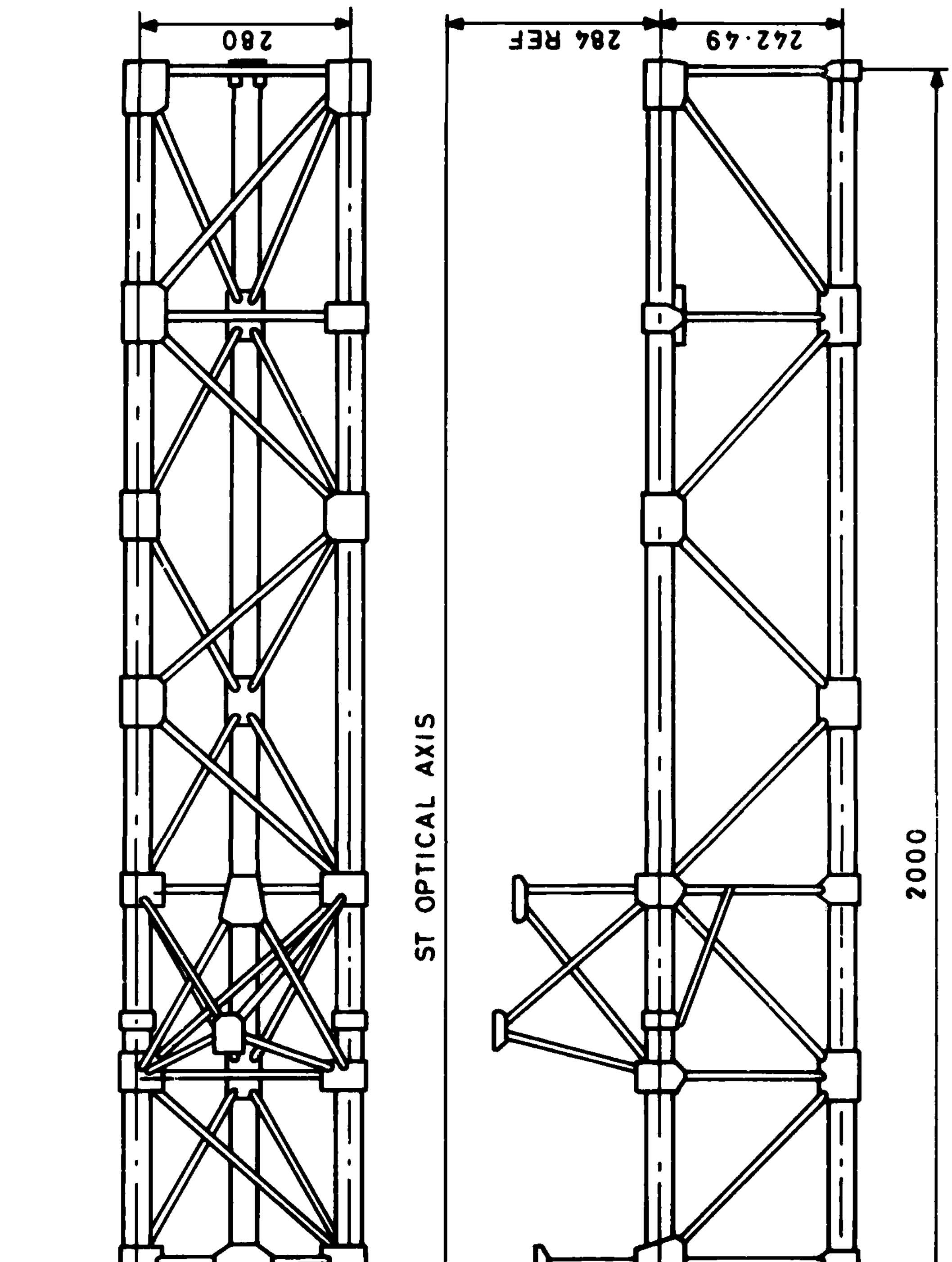


Fig.5 Faint object camera CFRP structure

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15. Abstract

The use of telecommunications spacecraft is expected to see a tremendous increase during the next decade. At the radio frequencies most likely to be commonly used, elastic deformation and thermal distortion can have significant effects on the accuracy and efficiency of the antennas. The Structures and Materials Panel of AGARD is therefore proposing to hold a future Specialists' Meeting on Dimensionally Stable Structures for Space to review structural and materials requirements for such antennas, and to discuss design and test methods and criteria. The three papers contained in this publication were presented at the Fall 1979 Meeting of the Panel as guidance in the planning of the forthcoming Specialists' Meeting.

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